WEATHER MODIFICATION

AN OPERATIONAL ADAPTATION PROGRAM FOR THE COLORADO RIVER BASIN

ATMOSPHERIC SCIENCE
LABORATORY COLLECTION

BUREAU OF RECLAMATION
Contract no. 14-06-D-6467

DEPARTMENT OF ATMOSPHERIC SCIENCE
COLORADO STATE UNIVERSITY
Fort Collins, Colorado

INTERIM REPORT FOR THE PERIOD
JULY 1968 - JUNE 1969

AN OPERATIONAL ADAPTATION PROGRAM OF WEATHER MODIFICATION FOR THE COLORADO RIVER BASIN

Interim Report
for the Period
July 1968 - June 1969

Bureau of Reclamation
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I. INTRODUCTION

This is an annual report of the efforts at Colorado State University to design a pilot program for operational weather modification in the Colorado River Basin. It includes: (1) A brief background description of the basis and need for a pilot program of operational weather modification, (2) A description of the procedures being followed in developing the design, and (3) A status report of the various phases of the design efforts.

Operational systems to enhance precipitation in some areas by 1972 was set as a goal by the Assistant Secretary of Interior in the November 1966 Bureau of Reclamation Planning Document for increasing water yield from atmospheric water sources. The Colorado River Basin Act passed in 1968, specifies further the Bureau of Reclamation's obligation to develop early means of water augmentation. The 1966 planning document includes an operational adaptation sequence for accomplishing this objective. This sequence calls for a progression of efforts from experimental to pilot and finally to fully "operational" projects. The term "operational," for purposes of the planning document, is used to describe projects after a useful capability is achieved and programs are undertaken for obtaining the benefits of an applied technology. This sequence of development of weather modification is consistent with the recommendation of the January 1966 report on weather and climate modification by the National Academy of Science National Research Council. One of the panel's recommended first steps was ". . . . the early establishment of several carefully designed, randomized seeding experiments, planned in such a way as to permit the assessment of seedability of various storm types." As outlined by the Bureau of Reclamation, this could represent an experimental-type program. In many areas such experimental programs have and are being established. In the case of the Upper Colorado River Basin, such an experimental program was established near Climax, Colorado, by Colorado State University in 1960 with the support of the National Science Foundation. This project is a carefully designed, randomized seeding experiment as recommended by the NAS Committee and permits assessment of the seedability of a variety of storm types. Additional experimental projects were established by the Bureau of Reclamation in the mid-1960's. One of these is the program at Elk Mountain in Southern Wyoming being carried out by the University of Wyoming. Another such program has been carried out by Bollay Associates over the Park Range in northwestern Colorado. The results from such experimental-type programs form the basis for progressing into pilot-type programs of operational adaptation envisioned in the operational adaptation sequence presented in the planning document. Results of a pilot-type project, initiated by the state of Colorado through Colorado State University, to adapt some of the results from Climax to the San Juan Mountains of southern Colorado are also available to provide background information.

The development of pilot projects, once the results of experimental projects became available, was also outlined in the planning document (1966). This called for preliminary studies for the design of field network requirements, procedures for seeding operation and techniques for evaluation. Preliminary studies to form the basis for pilot projects have been carried out by the internal staff of the Office of Atmospheric Water Resources at the Bureau of Reclamation. This annual report describes the contracted efforts by Colorado State University to prepare a specific design for pilot projects within the Basin.

Early phases of the design study were directed toward (1) the selection of an area for the initial pilot project, and (2) the determination of the basic requirements for an observing network. The area for an initial pilot project has been tentatively designated by the Bureau of Reclamation. The initial stage of the establishment of an observation network is now in progress by Western Scientific Services, Inc., under a direct contract from the Bureau of Reclamation.

The primary emphasis in the design preparation is concerned with the technical aspect of the pilot project. This includes the definition of the physical basis for the program, the establishment of the methodology to be employed, and the formulation of evaluation procedures for establishing the amount of water added. For the program to have proper perspective, many other aspects are also being considered. These include various vital matters of basin hydrology, together with economic, social, and political considerations. The efforts this first year have concentrated on background studies of the many facets of the program. This first annual report serves as a review of the progress of this work. These background studies have not yet been incorporated into a fixed design for the pilot program, except for some phases of the program, such as those dealing with the area selection and some of the basic field observation requirements. Formalization of operating and evaluation procedure will take place during the coming year based largely on background studies already completed or underway.

II. OBJECTIVES

A pilot program of weather modification for the Colorado River Basin is clearly intended to serve as a transition from experimental to fully applied programs. The detailed objectives of this program have been stated in a number of forms. Several different ways in which the objectives have been stated are included here in an attempt to cover the full scope of the objectives envisioned for the program.

The objective of the design study for an operational adaptation program for the Colorado River Basin, as stated in the contract between the Bureau of Reclamation and Colorado State University, is: "The objective of this undertaking is to develop the design for a pilot program of operational cloud seeding research in the Colorado River Basin, to add basic information to the sciences of cloud physics and weather modification, and advance technology pertinent to the operational aspects of weather modification for increasing water supplies within the Basin." This has been elaborated on by the Bureau of Reclamation in the following description: "The main objective of the Colorado River Basin pilot project is to provide sound scientific engineering evaluation of precipitation increases over a large area by an operation-type application of cloud seeding techniques employed and criteria developed through the Climax, Colorado, experiment. The evaluation and analyses of project data will also furnish a more detailed climatology of natural precipitation occurrences over mountainous areas, improved identification of precipitation increase during different seedable conditions and its distributions over large mountain massives, and an accounting of costs involved. The project will also afford an important opportunity for assessing social-environmental problems associated with weather modification operations and for appraising technical performance factors. These objectives are oriented toward learning definite answers on the technological factors and feasibility considerations involved in producing large quantities of additional streamflow in the Upper Colorado River Basin. Studies of the associated social and environmental considerations will be made in conjunction with the pilot project to define any problems and suggest means for resolving them. Field experiments independent of the pilot project in other areas of the Upper Basin and adjoining regions will furnish additional climatological data and seeding experiments to supplement the pilot project findings" (Private correspondence from A. Kahan, 1969).

Pilot models or pilot programs serve as a transition from research and/or development to applied programs and/or devices. The need for further engineering and/or research usually becomes apparent in development and/or construction of such pilot models. A pilot model for weather modification requires such extensive efforts to evaluate that research will inevitably be incorporated. The authors interpret their objective as the design of a pilot model of a field program of applied cloud seeding for increasing water supplies in the Colorado River Basin based on contemporary knowledge. Evaluation procedures for such a program must include a reasonable estimate of the water produced from the program at stated confidence levels and an assessment of the technology employed. The considerable costs and efforts involved in weather modification field programs dictates that the design also provide for maximizing the amount of information for subsequently improving the procedures employed.

The objective of the pilot project studies might also be described as a field test of weather modification within the Upper Colorado River Basin using criteria developed in experimental programs. When applied to a target area of a 1,000 to 3,000 square miles, this field test should (1) provide with a specified confidence the number of acre feet of water added, (2) establish the cost per unit volume of the water added, and (3) provide basic scientific and technological information that can be used in upgrading subsequent programs.

III. ORGANIZATION OF THE DESIGN STUDY

The design of the pilot program is under the overall direction of Lewis O. Grant and Paul W. Mielke, Jr., of the Atmospheric Science Department and the Mathematics and Statistics Department, respectively, of Colorado State University. Supervision of the work in progress and coordination with the Bureau of Reclamation is being handled by Charles F. Chappell also of the Department of Atmospheric Science, Colorado State University. Mr. Chappell is also primarily responsible for the studies and reports related to the physical basis for cloud seeding in the Colorado Rockies, the delineation of meteorological criteria critical to weather modification in this Basin, portions of the climatic studies, and development of forecasting procedures for the significant criteria. The following additional professional personnel are directly involved in overall program planning and implementation. The specific aspects of the program for which they accept primary responsibility for work progress and reports are also shown:

a. Mr. Loren Crow, Consulting Meteorologist, basin geography, maps, climatology
b. Dr. James Rasmussen, CSU, atmospheric water balance, utilization of satellites
c. Dr. William Marlatt, CSU, remote sensing
d. Mr. Homer Stockwell, CSU, hydrology
e. Dr. Ron Wykstra, CSU, economics

The efforts of Colorado State University are confined to design studies. This does not include project implementation or field observations. The following consultants have reviewed the original work outline:

a. Mr. R.D. Elliott, North American Weather Consultants
b. Dr. James McDonald, University of Arizona
c. Dr. Vincent J. Schaefer, State University of New York

The program has also been discussed in detail with the following experienced researchers in such weather modification design problems:

a. Dr. A.M. Kahan, Pat Hurley, and other Bureau of Reclamation personnel
b. Dr. Larry Davis, EG&G
c. Dr. Richard Schleusener, South Dakota School of Mines & Technology
d. Dr. Donald Veal, University of Wyoming

Many constructive comments were received at the February 11 and subsequent meetings at the Bureau of Reclamation. The comments of Dr. Julian Bigelow during March and April have been particularly beneficial.

IV. PROCEDURES

A. Design Efforts

The design efforts can be classified into four broad categories. The first is concerned with the basic design of the overall program. The second involves definition of operational opportunities since this is so critical to the design of such a program. The third pertains to the operational procedures to be employed. The fourth includes control procedures for actual field operations.

1. Program Design
   This involves the development of a design, incorporating both experimental and applied aspects of precipitation management. The design must provide for real time interpretation of results and subsequent detailed evaluations but still be flexible enough to incorporate new concepts as they become available.
2. Operational Definition
   This phase of the program considers the identification and definition of atmospheric and climatological variations of conditions which affect the control of the effectiveness of precipitation modification activities. It also includes the development of criteria and forecast procedures to predict suitability for modifying various weather situations and the definition of varying seeding techniques which might be employed.
3. Operational Design
   This phase involves consideration of procedures and techniques for carrying out the designed field cloud seeding program using present technology but with provisions for the incorporation of new technology as it develops, and for the systematic expansion of the program. It also includes consideration of specific sensing and data acquisition system requirements, definition of seeding materials and delivery system requirements, considering alternatives and relative merits of each, and the development of models that can serve as the basis for making operational decisions.
4. Operational Control
   The importance of the control of the field operations once the pilot program is initiated is of such importance that it is included as the fourth phase of the planning program. This incorporates procedures and logic for handling information from sensing systems, making operating decisions, real time interpretations, and carrying out analyses of the activities in progress. It is envisioned that as the program develops a large computer will be available to an operations control center. Current field information would be fed into the computer system which, when combined with stored information programs, could rapidly be used to provide necessary analyses. It is envisioned that the output from the computer models would take the following general sequence:

a. Determination of the natural precipitation possibilities
b. Determination of the suitability for modification
c. Analysis of the economic implications. (This would include the consideration of the streamflow response to be expected and other economic effects of the operation for determination of cost-benefit interpretations with different operational alternatives.)
d. Interpretation and description of operational procedures to employ
e. Real-time evaluation of efficiency of the field program and, to the extent possible, the effectiveness of the operation
f. The form of the output would be designed to facilitate post-operational evaluations

B. Specific Comments on Some of the Vital Aspects of the Design

It is not the purpose of this report to describe in detail the approach being followed in each phase of the effort. The following is intended to provide a brief description of some of the specific items receiving consideration:

1. Program Design
   a. Delineation of operational areas
      (1) Preparation of suitable maps
      (2) Definition and description of the suitability of various sub-areas of the Colorado River Basin for a pilot program
      (3) A description and determination of the availability of required facilities in the various sub-areas

      While river watersheds are referred to above in some cases, the sub-areas to be seeded are defined strictly in terms of mountain massives and not as specific drainage basins. The orographic uplifting occurs over the mountain barrier and all drainage basins originating from that barrier are considered in the planning of the weather modification efforts.
   b. Economic and social considerations
      (1) Hydrology
      (2) Direct water uses
         (a) Dry land
         (b) Grazing
         (c) Forest uses
         (d) Water quality
         (e) Recreation
      (3) Relation to human activities
      (4) Seeding contamination
         (a) Inadvertent modification
         (b) Effects from upwind seeding operations
         (c) Downwind effects of pilot program operations
      (5) Relationship to research experiments
         (a) Spatially influenced activities
         (b) Technologically related activities
   c. Operational control and evaluation

      The program is being designed to establish operations based on physical models of orographic cloud processes when possible and extending these when feasible, utilizing empirical considerations.

      Four alternate evaluation procedures for establishing the effects of seeding are being developed. These are designed to determine:
      (1) Changes in vital steps in the physical model
      (2) Changes with time of the atmospheric water balance
      (3) Changes in precipitation utilizing statistical techniques
      (4) Changes in hydrologic parameters utilizing statistical techniques
2. Operational Definition
   a. Establish criteria for operations
      (1) Precipitation events
      (2) Modification potential
   b. Climatology
      (1) Meteorological parameters
      (2) Modification criteria
3. Operational Design
   a. Observation network for data input
      (1) Surface
      (2) Upper air
      (3) Satellite
   b. Determination of operational seeding equipment to be employed:
      (1) Surface
      (2) Aloft
   c. Seeding agents
   d. Targeting of seeding operations
   e. Communications and telemetry
   f. Transportation
   g. Cost control
   h. Description of techniques for using present technology to meet requirements of physical models of the cloud systems
4. Operational Control
   a. Administrative and technical channels for controlling operations
   b. Control central and field bases

      Optimum control of the observational and seeding activities will require very substantial amounts of input and stored information with a requirement for substantial processing. The pilot program should be controlled from a central base that would have immediate access to a large computer. It is visualized that certain basic hydrometeorological data will be telemetered into the control central and immediately made available for computer processing and interpretation. While the main control base should be in the general proximity of the field programs, it is not considered essential that this base be located within the pilot project area. Field bases, however, would be required for supplying crucial operational information and servicing equipment.

c. General procedures (computer model) for controlling operations
   (1) Input data for the computer model
      (a) Weather system description
         [1] Macroscale
         [2] Mesoscale
         [3] Microscale
      (b) Stored data programs
         [1] Opportunity definition
         [2] Seeding equipment capabilities
         [3] Delivery capabilities
         [4] Watershed and streamflow characteristics
         [5] Cost-benefit relationships
         [6] Etc.
      (c) Computer output as shown under item 4 of the first portion of this section of the report.

V. STATUS REPORT ON VARIOUS PHASES OF THE OPERATIONAL ADAPTATION PROGRAM FOR THE COLORADO RIVER BASIN

A. Physical basis for weather modification operations

1. Introduction

Since Wegner (1911) first suggested the rapid growth of ice crystals within supercooled water clouds, the artificial stimulation of precipitation was believed possible under certain conditions. After Schaefer (1946) demonstrated the conversion of a supercooled water cloud to ice in a cold chamber utilizing dry ice, and Vonnegut (1947) reported a method for nucleating ice formations in the atmosphere, attempts at precipitation augmentation began in earnest.

The physical basis for treating cold orographic clouds by seeding was presented by Bergeron (1949), and discussed in more detail by Ludlam (1955). The orographic induced clouds along and windward of the mountain ranges over the western United States are frequently composed of supercooled liquid droplets. The temperature activation spectrum of natural nuclei is such that the number of effective natural ice nuclei may not meet cloud requirements for converting the cloud water to ice form at the warmer cloud temperatures and higher condensation rates. In such cases snow may not develop, or the precipitation process may be inefficient. If artificial ice nuclei can be activated in the saturated orographic stream far enough upwind of the mountain barrier, a more efficient conversion of cloud water to ice crystals should result in increased snowfall. Otherwise, the unconverted cloud water evaporates to the lee of the mountain barrier. Modification potential (type I) can exist from a difference in the supply rate of condensate and the growth rate of ice in the cloud system, and is related to the evaporation rate of the cloud system.

Other potential for modification (type II) exists if, by treating the cloud system, an additional latent heat release can affect a change in the condensation rate itself by altering the vertical motion field. It seems this type of modification potential would mainly coexist with that of type I. If the conversion of cloud water to ice form is transpiring at an optimum efficiency, little lasting change in the latent heat release can be affected by adding additional ice nuclei. Seeding under this condition should result in only small effects related to altering the size of the snow crystals growing in the cloud system. Through this paper "modification potential" will connote the type I meaning described above.

A simple model presented by Grant et al., (1968) showed roughly the variation of optimum ice nuclei concentrations as a function of cloud system temperatures. The optimum ice nuclei concentration was defined as that which enabled the cloud system to grow ice by diffusion at a given condensation rate. Preliminary results of the Climax, Colorado, weather modification experiment for the years 1960-65 showed the distribution of seeding effects with 500 mb temperature followed the trend indicated by the model.

Following a similar approach a more refined and improved model is derived by Chappell et al.(1969) that is tailored for existing cloud conditions at Climax and Wolf Creek Pass, Colorado. Features of the model are appraised utilizing natural snowfall observations from the two experimental sites. Finally, the results from independent data samples acquired during cloud seeding experiments conducted at the Climax and Wolf Creek Pass areas are compared for consistency and discussed relative to the improved model.

2. A Model to Delineate Modification Potential

The major assumptions embodied in the model to be derived are (1) the rate of extraction of cloud water by growing ice crystals is mainly by diffusional growth, (2) the supply rate of cloud water is adequately defined by parcels following a pseudoadiabatic process, and (3) the cloud system is embedded in the 700 mb to 500 mb layer with a vertical temperature distribution equivalent to the moist adiabatic lapse rate.

Refinements in the model include the incorporation of observations at Climax to evaluate factors in the diffusional growth equation that were not included originally. Also, all variables of temperature have been expressed in terms of the temperature at the 500 mb level. The incorporation of diffusional growth only into the model is substantiated by snow crystal samples collected at Climax. These snow crystal replicas rarely show appreciable riming. Furman (1967) has also shown that the tops of clouds during snowfall at Climax are generally near the 500 mb level.

a. Rate of ice growth by vapor diffusion

If it is assumed that around a growing ice crystal there is a steady state diffusion of water vapor and steady state thermal conduction, the rate of ice crystal growth by vapor diffusion is usually expressed as

$$dm/dt = 4\pi C \rho_i S_i G' F_1 F_2 \qquad (1)$$

where

$$G' = D(\rho_v/\rho_i)[1 + DL_i^2 \rho_v / R_v T^2 K]^{-1} \qquad (2)$$

and m is the mass of an ice crystal; C the electrostatic capacity factor of the crystal; S_i the supersaturation relative to a plane ice surface; L_i the latent heat of sublimation; R_v the gas constant for saturated air; D the diffusion coefficient; K the thermal conductivity of air; ρ_v the vapor density; ρ_i the ice density; T the ambient temperature; F_1 the ventilation factor of the crystal in the air flow; F_2 the vapor factor that corrects the vapor field to that of a supercooled cloud.

The ventilation factor may be written as a function of the Reynold's Number or

$$F_1 = 1 + .22 R_e^{\frac{1}{2}} \qquad (3)$$

The Reynold's Number is defined by

$$R_e = 2Vr_e/\nu \qquad (4)$$

where V is the velocity, r_e is the equivalent radius of a crystal having the same volume as a droplet, and ν is a kinematic viscosity.

The equivalent radius of a crystal is determined from the relation

$$r_e = \tfrac{1}{2} a^{2/3} c^{1/3} \qquad (5)$$

where a and c refer to the lengths of the crystal axes. Combining (3), (4), and (5) the ventilation factor may be expressed

$$F_1 = 1 + 0.22 (Va^{2/3} c^{1/3}/\nu)^{1/2} \qquad (6)$$

From (6) it is seen that the ventilation factor in the growth equation is a function of the crystal habit and size, crystal fall speed, and the kinematic viscosity. Through the habit and viscosity terms the ventilation factor is dependent upon pressure and temperature.

For simplification a mean value of the ventilation factor may be computed for conditions that frequently occur at Climax. The settling velocity relative to the environment is taken a at 60 cps, and a value of 0.18 is given the kinematic viscosity. This value is applicable for a pressure of 700 mb and a temperature of -10C.

After substituting these values into (6) the ventilation factor is found to equal about 1.7.

Marshall and Langleben (1954) derived a factor (F_2) that corrects the vapor field to that of a supercooled cloud. An expression for this vapor factor may be written

$$F_2 = 1 + r(4\pi \textstyle\sum_1 r_c)^{\frac{1}{2}} \qquad (7)$$

where r is the radius of an ice crystal and r_c is the cloud droplet radius.

It is seen from (7) that the vapor factor is a function of the size of the growing snow crystal and the sum of all cloud droplet radii per unit volume.

For simplification a mean vapor factor may be evaluated for conditions representative of the snowfall and continental type clouds present in the Climax area. A mean radius for snow crystals of about 400 microns is taken, and a mean cloud droplet concentration of 200 per cm^3 having a mean droplet radius of 6 microns is assumed.

Substituting these values into (7) gives a value for the vapor factor of about 1.05.

The electrostatic capacity factor (C) is a function of the crystal shape. Based on typical temperatures found in winter orographic clouds it is reasonable to consider that the capacity factor may be approximated by that of a circular disk, or $C = 2r/\pi$.

Substituting the values for the ventilating factor (F_1), vapor factor (F_2) and capacity factor (C) into (1) the diffusional growth equation becomes

$$dm/dt = 14.4 r[SG'\rho_i] \qquad (8)$$

In the case of a crystal growing in an environment at water saturation the bracketed quantity in (8) may be solved as a function of temperature (Mason, 1953) and is henceforth denoted F(T). From (8) it can be noted that the growth by vapor diffusion of a crystal in an environment at water saturation has been reduced to a function of crystal size and cloud system temperatures.

b. Supply rate of condensate

The determination of the rate at which cloud water is supplied within an orographic cloud system is quite complex since it depends upon a knowledge of the vertical motion fields over the mountain barrier. This complexity partially stems from the vertical motion field which may be composed of three components: orographic, dynamic and convective.

The orographic component depends mainly upon the direction and speed of the wind flow relative to the orientation of the mountain barrier, stability, of the air mass crossing the barrier, and the nature of the vertical wind shear present. The dynamic component is controlled by the vertical distributions of mass divergence associated with traveling disturbances in the westerlies. On occasion the thermal instability of the air mass present may result in the development of convective cells and lines having concentrated and significant vertical motions.

For purposes of demonstrating important aspects of modification potential a mean orographic component may be estimated and treated as a known parameter.

Following this approach the rate of condensation production per unit volume in the cloud system can be expressed as

$$C_a = 1.11\,(10^{-9})\,\omega\,(q_{s_{700}} - q_{s_{500}}) \qquad (9)$$

where ω is the mean upward speed in mb per hour, q_s is specific humidity at water saturation in gm per kgm, and C_a is expressed in gm per sec liter. From (9) it is seen that the rate at which liquid water is supplied in the cloud system is a function of the upward air speed and cloud system temperatures.

c. Relation of ice crystals to cold cloud precipitation efficiency

For maximum utilization of cloud moisture in the cold cloud precipitation process it is desirable to have the integrated growth rate of the ice crystals per unit volume (N_c) proceed at the identical rate as the cloud water is supplied per unit volume by the condensation process. This condition can be expressed by equating (8) and (9). The optimum ice crystal concentration can then be expressed as

$$N_c = 7.7\,(10^{-11})(\omega/r)[(q_{s_{700}} - q_{s_{500}})/F(T)] \qquad (10)$$

where N_c is the number of ice crystals per liter.

It is apparent from (10) that no unique ice crystal concentration is associated with a maximum utilization of cloud water since the radius of the ice crystal remains a variable. For a given upward speed in the cloud system the ultimate crystal size can adapt to the concentration of growing crystals for best utilization of cloud moisture.

There are practical boundary conditions that confine desired adjustments between crystal size and concentration. The number of crystals could increase until crystal size ultimately is so small that the settling velocity of the crystal is radically reduced. In this event, the crystal could be carried over the mountain barrier without deposition. Evaporation of this moisture in the lee of the mountain would then represent a loss of precipitation below that which would have fallen naturally.

The extreme limiting condition is reached if the crystal concentration becomes so large that the ultimate crystal size attained results in complete suspension of the tiny crystals.

The other boundary condition limiting the interplay of crystal size and concentration arises when required crystal sizes for maximum utilization of cloud water become too large. Under these conditions the crystal may be unable to remain in the cloud system for a sufficient growth period, or the accretion process may begin to remove important amounts of cloud water.

The possibility of targeting snowfall is quite interesting. If the crystal size adjusts to the crystal concentration then some control can be exerted over the crystal trajectory. This might come from either affecting the crystal settling speed directly, or indirectly by promoting agglomeration.

Solutions to (10) can be obtained as a function of the 500 mb temperature for specific upward speeds and representative ice crystal sizes. A mean upward speed applicable to the Wolf Creek Pass area is estimated to be about 50 cps. This is obtained by taking the mean wind speed (15 mps) observed in the 700 mb to 500 mb layer during snowfall, and multiplying by the terrain grade toward the southwest (.063). This results in a value approximately equal to 1 mps. Since a mean upward motion for the cloud layer is desired, and upward speeds must approach zero toward the upper limit of the cloud, the 1 mps is reduced by one half, or 50 cps.

In order to obtain a representative mean upward speed for the Climax area, the ratio of the average hourly snowfall at Climax to the average hourly snowfall at Wolf Creek Pass is multiplied by the 50 cps upward speed derived for the Wolf Creek area. This ratio is about one third resulting in an estimate of the mean vertical speed for the Climax area of 15 cps. This indirect approach was taken for the Climax area because of the very complex terrain features located in that area.

Figure 1 shows various solutions to (10) for upward speeds of 15 cps and 50 cps, and crystal radii of 100 microns, 300 microns and 500 microns.

Figure 1 indicates that at colder temperatures the required concentrations of ice crystals nearly stabilizes for a given crystal size and upward speed. This stabilization reflects the region where the amount of moisture supplied decreases at nearly the same rate as the capacity of the crystal to grow. The optimum concentration of ice crystals required increases rapidly for a given crystal size and upward speed as 500 mb temperatures become warmer than about -14C. This is due to the increasing water supplied at these warmer temperatures coupled with slower crystal growth rates which results in an accelerating need for more ice crystals to utilize the cloud water.

d. Temperature activation spectrum for ice nuclei

The number of ice nuclei activating in the atmosphere is highly variable in time and space. In general most observations have indicated a crude exponential rise in ice nuclei counts with decreasing temperature. An average spectrum of ice forming nuclei in the atmosphere may be determined from the relation

$$N_N = (10^{-5})\,e^{-0.6T} \qquad (11)$$

where T is the temperature in degrees centigrade

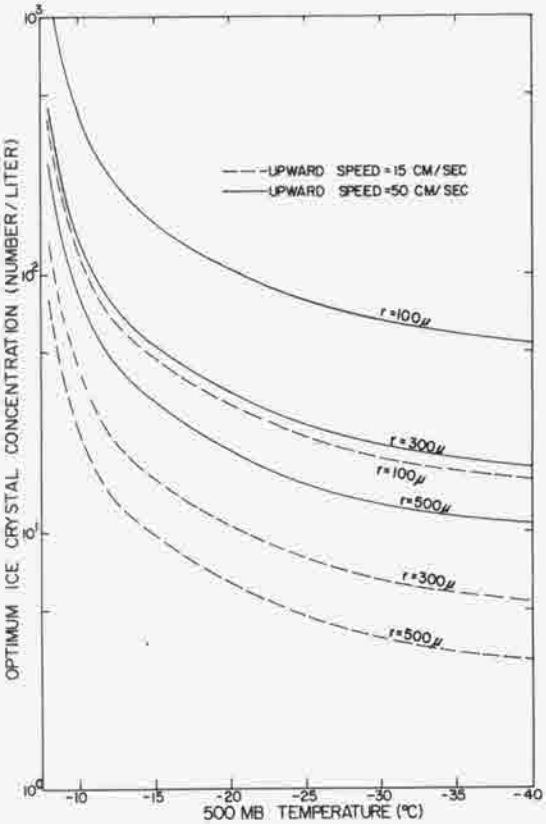


Figure 1. --Relationship of ice crystal concentration, ice crystal size, cloud top temperature, and vertical motion which optimizes the efficiency of cloud water utilization.

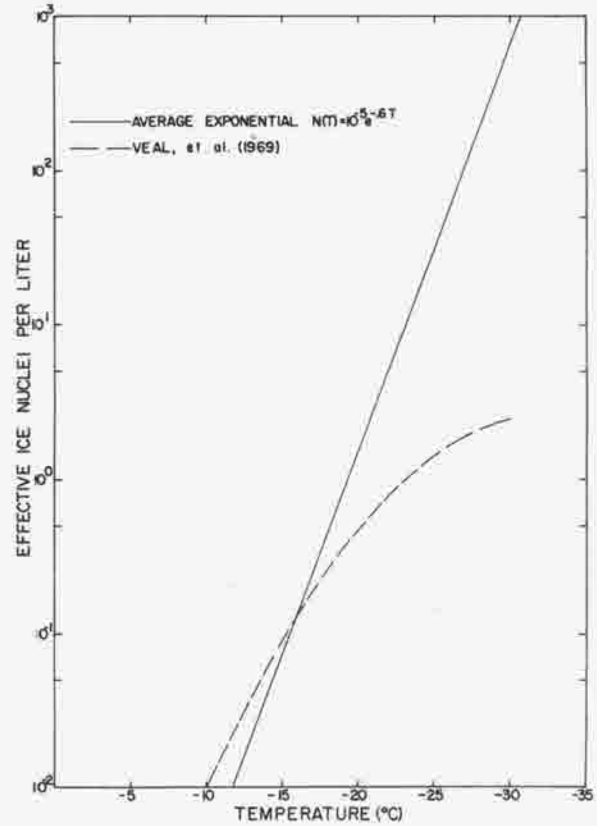


Figure 2. --Concentration of effective ice nuclei as a function of temperature.

and the concentration is expressed in particles per liter. This relation is shown in Figure 2. It is emphasized that this is an average spectrum of ice nuclei and actual counts may differ an order of magnitude or more at a given time or place.

Some observations have indicated the existence of a "plateau," or leveling off of the ice nuclei counts in the temperature range from -20C to -30C followed by sharp increases at temperatures below -30C. This effect has most recently been found by Veal, et al. (1969) for cap clouds in southern Wyoming. Since average ice nuclei counts taken at Climax for temperatures near -20C are in general agreement the average exponential activity spectrum will be invoked as representative of conditions in the Colorado Rockies.

e. Ice crystal imbalance in precipitating cold orographic clouds

One further bit of information is needed before estimates can be made of the number of artificial ice nuclei required for maximum cloud water utilization. A vital point to be clarified is the number of ice crystals that will be generated for each ice nuclei activated within the cloud system. The ratio of these concentrations is a critical control on whether a potential for modification exists with the cloud system. If this ratio of ice crystal concentration to ice nuclei concentration (R) is multiplied by the effective ice nuclei concentration given in (11), and the optimum ice crystal concentrations expressed by (10) are subtracted, an expression for ice nuclei excess or deficit may be obtained. This relation is given by (12)

$$\Delta N=R(10^{-5})e^{-.6T}-7.7(10^{-11})[\omega/r][(q_{s_{700}}-q_{s_{500}})]/F(T)]$$

For a given upward speed, crystal size and ice crystal to ice nuclei ratio, the excess or deficit of ice nuclei may be depicted as a function of the 500 mb temperature. Curves are shown in Figure 3 for a one to one correspondence of ice crystal concentration to ice nuclei concentration, and for mean upward speeds and crystal sizes relevant to the Climax and Wolf Creek Pass areas.

It is seen from Figure 3 that the maximum utilization of cloud water for a mean upward speed of 50 cps and crystal radii from 300 microns to 500 microns (estimated to be representative of the Wolf Creek Pass area) occurs at 500 mb temperatures from -23C through -25C. These temperature values are defined in Figure 3 where the relevant curves intersect the zero axis (actually the 0.1 excess or deficit axes since a log scale is utilized). For an upward speed of 15 cps and crystal radii of 300 microns to 500 microns (a size range frequently observed at Climax) the natural precipitation process attains an optimum mode at 500 mb temperatures from -21C through -23C. The increase in mean upward speed from 15 cps to 50 cps has the effect of shifting the mode of maximized precipitation efficiency 2C toward colder temperatures.

It is apparent from Figure 3 that for all crystal sizes and upward speeds depicted, the naturally effective ice nuclei excess is one hundred or more for 500 mb temperatures of -28C and colder. Also, for the conditions displayed there is a deficit of effective ice nuclei at all 500 mb temperatures warmer than -21C. At -15C the effective ice nuclei deficits range from 10 to 165 per liter.

The assumption of an ice crystal to ice nuclei ratio of one is open to question. Results of investigations by Mossop et al., (1967, 1968, 1969), Hobbs (1969), Veal et al. (1969), and Grant (1968) are shown in Figure 4. If the results of Grant and Hobbs are neglected for the moment, the remainder of the observations indicate an average exponential increase of the ratio with temperature (middle diagonal line in Figure 4). This is a most interesting result. If this relation is substituted into (12), the net ice crystals realized in the cloud system as a function of temperature completely erases all ice nuclei deficits for conditions depicted in Figure 3. The incorporation of this relation into the model therefore eliminates all potential for modification in the range of conditions

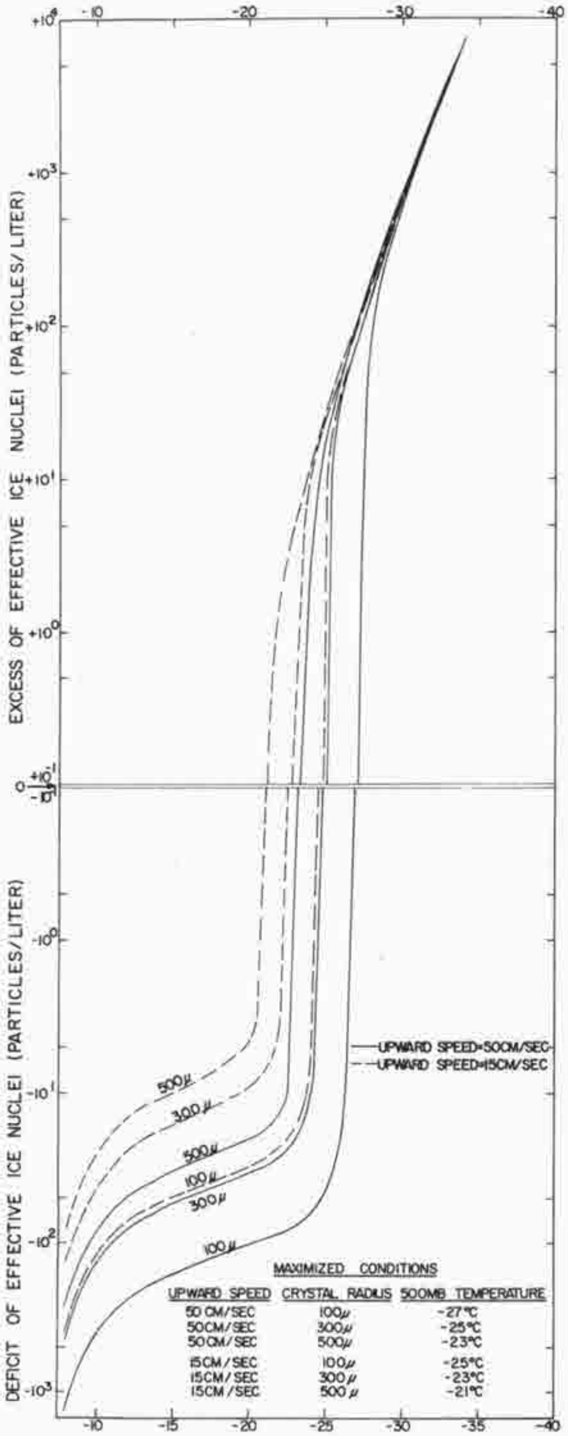


Figure 3. --The deficit (below) and excess (above) in effective ice nuclei concentration required to optimize the precipitation efficiency for various crystal sizes and upward speeds as a function of the cloud top temperature.

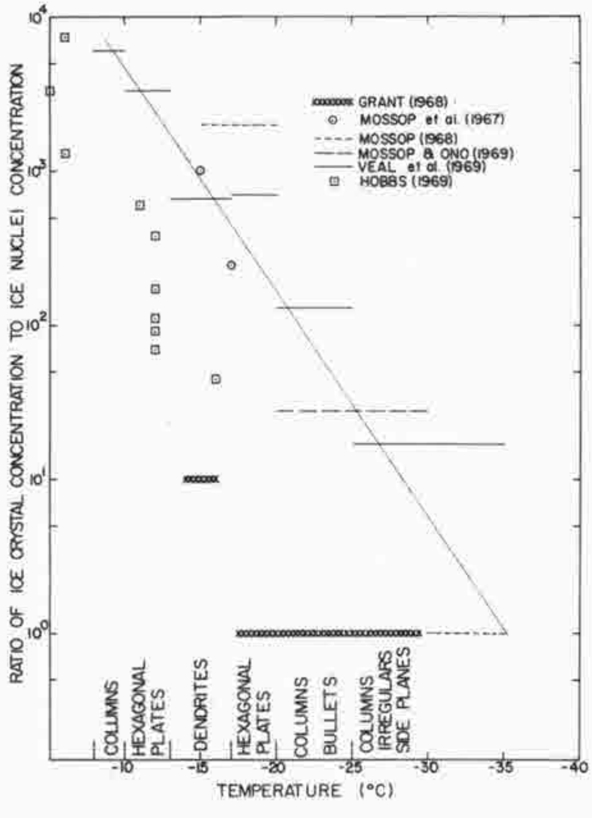


Figure 4. --Relationship between the ratio of ice crystal concentration to corresponding ice nuclei concentration as a function of temperature. Crystal habits according to Magono and Lee (1966).

considered. A knowledge of this ratio is therefore vital to the definition of modification potential in cold orographic clouds.

The study of Grant (1968) suggests that occasionally the ice crystal to ice nuclei ratio may attain a value of about ten at Climax in the temperature range where dendritic crystals would be expected to form in the upper portion of the cloud system. If the results of Grant are incorporated into the model, the overall picture of requirements for modification is hardly changed. From Figure 3 it is seen that a value of ten for the ratio at 500 mb temperatures about -15C would reduce, but not eliminate the modification potential for most conditions displayed. The natural snowfall process at Climax and Wolf Creek Pass, Colorado, is now investigated for further evidence pertinent to a solution of this question.

f. Relationship of mean daily snowfall to cloud top temperature

Mean daily snowfall was computed as a function of the 500 mb temperature for two winter seasons at Wolf Creek Pass and for five years at Climax, Colorado. Only non-seeded precipitation was used in this study. The precipitation data recorded at Wolf Creek Summit and Wolf Creek West stations were pooled to increase the available sample. The mean daily snowfall was computed utilizing a running mean over a two-degree temperature interval. Figure 5 shows the results of this study.

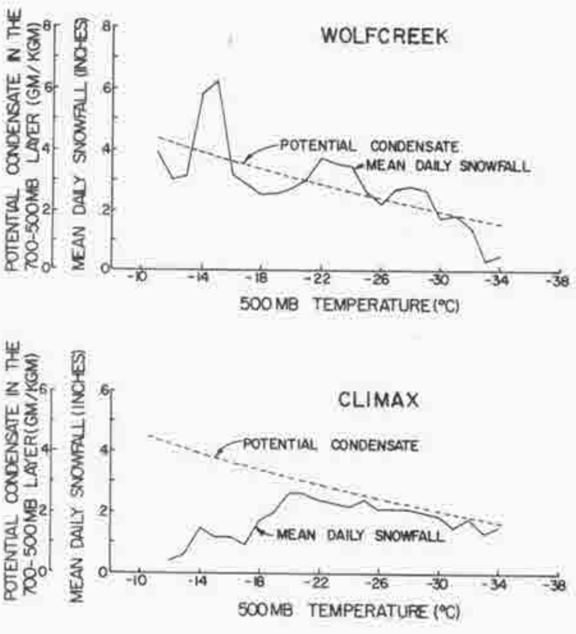


Figure 5.--Mean daily snowfall related to cloud top temperatures (500 mb) at Climax and Wolf Creek Pass, Colorado. Snowfall is computed using a running mean over a two-degree temperature interval.

A peak in the mean daily snowfall is evident in the 500 mb temperature range from -22C to -24C at Wolf Creek Pass with amounts decreasing as cloud top temperatures become colder. This decrease is mainly due to the reduction in the potential condensate of the cloud system. This is illustrated by the dashed lines in Figure 5. These lines show the amount of condensate that would be produced by a parcel moving upward through a 700-500 mb saturated layer. The peak in the mean daily snowfall at -22C to -24C appears to reflect a 500 mb temperature mode where on the average the available effective ice nuclei and the cloud water supplied combine to maximize the precipitation.

The decrease in mean daily snowfall as 500 mb temperatures become warmer than -22C is interesting. The mean daily snowfall decreases steadily from -22C to -18C in spite of an increase in potential condensate for these cloud systems. This suggests the natural precipitation process is becoming more inefficient through this temperature range, probably due to a growing deficit of effective ice nuclei in the cloud system. These observations are consistent with the trends suggested by the model shown in Figure 3. For estimated Wolf Creek Pass conditions a 500 mb temperature mode that maximizes the natural precipitation is found at -23C through -25C. Growing deficits or excesses of effective ice nuclei are indicated at temperatures above and below this range respectively.

The marked increase of mean daily snowfall at Wolf Creek Pass for 500 mb temperatures around -14C to -15C is striking. This pronounced peak in amounts probably reflects a temperature mode where dendritic crystals form in the upper portion of the cloud system. This could result in fracturing of the dendritic crystals and an ice multiplication process. This apparently occurs occasionally at Climax (Grant, 1968). This increase in the ice crystal to ice nuclei ratio from about one to ten or more would increase the efficiency of cloud water removal and result in natural precipitation increases.

It is interesting that the mean daily snowfall appears to decrease again at the warmest cloud top temperatures contained in the sample (-11C to -13C). However, these events are near the tail of the distribution and have limited sample sizes.

Figure 5 also shows the mean daily snowfall at Climax. This curve was generated similarly to the Wolf Creek Pass diagram. The mean daily snowfall at Climax indicates a 500 mb temperature mode that maximizes the natural precipitation from -20C through -22C. This is about 2C warmer than found for the Wolf Creek Pass area.

The snowfall trend at Climax follows closely the potential condensate in the 700-500 mb layer from -34C up to -20C. From -20C to -17C the mean daily snowfall decreases abruptly in spite of the rise in potential condensate. A minor secondary peak is in evidence at about -14C followed by apparent decreases again at the warmest temperatures.

The Climax and Wolf Creek Pass curves are somewhat similar. The major differences appear to be a slight shift of the mean daily snowfall peak toward warmer temperatures and a less pronounced peak around -14C to -15C for the Climax data. The reduction of mean daily snowfall at the warmer temperatures is less pronounced for the Wolf Creek Pass sample. This may be due to accretion which is observed with greater frequency in the Wolf Creek Pass area.

The shift toward warmer temperatures of the mean daily snowfall peak at Climax is anticipated by the model. Figure 3 shows that for representative Climax conditions the 500 mb temperature mode that provides optimum ice nuclei concentrations is from -21C through -23C. Assuming the secondary peaks of daily snowfall around -14C to -15C are a result of dendritic growth, the more pronounced effect at Wolf Creek Pass might be explained by a greater frequency of cloud systems having higher supersaturations and somewhat more maritime characteristics.

The distribution of natural precipitation with respect to 500 mb temperatures suggests a deficiency of effective ice nuclei may exist in the warmer cloud systems. This deficit may on occasion be alleviated by an ice crystal multiplication process in the dendritic range around -15C. This is much more in evidence at Wolf Creek Pass than at Climax. A ratio of ice crystal concentration to corresponding ice nuclei concentration that increases exponentially with temperature is not reflected in the natural precipitation data from Wolf Creek Pass and Climax. Therefore, artificial augmentation of natural snowfall at warmer cloud top temperatures and when high cloud water supply rates exist appears probable.

g. <u>The accretion process</u>

Equation 10 can be written as

$$Nc = (k)f(\omega/r)\,G(T) \qquad (13)$$

where Nc is the optimum ice crystal concentration, k is a constant, ω is the vertical motion in pressure coordinates, r is the radius of the ice crystal and G(T) is a function of the cloud system temperature.

As pointed out previously, the crystal size is free to adapt to changes in the cloud water supply due to variations in the upward speed. Thus, additional ice crystals may not be needed to utilize increases in cloud water if larger crystal sizes can be grown. A limiting condition comes into play, however, when the crystal size required to maximize the precipitation process becomes too large. Under these conditions the crystals may be unable to remain in the cloud system for a sufficient growth period or the accretion process may begin to contribute significantly to cloud water removal. The residence time of ice crystals is frequently limited by the relatively small horizontal extent of orographic clouds over the mountains. Therefore, there is frequently an upper limit placed on the crystal size by the geometry of the orographic cloud. This restriction on crystal size not only tends to limit the amount of cloud water that can be removed by diffusional growth of ice, but also affects possible accretional growth. The reason is that the amount of cloud water removed by accretion is also a function of ice crystal size. This is seen in the expression for the rate of mass growth of a falling crystal by accretion usually given by

$$dm/dt = \pi r^2 E(V_c - V_d)\,Q_c \qquad (14)$$

where r is crystal radius, Q_c is liquid water content, $(V_c - V_d)$ the difference in fall velocities between crystal and supercooled droplet, and E the collection efficiency.

In utilizing equation (14), it is usually assumed that $V_d << V_c$. The collection efficiency E of ice crystals is not well known. It is not only a function of crystal size but of crystal habit and therefore is related to cloud system temperatures.

The crystal radii associated with the onset of riming are generally noted to be in the range of 100μ to 400μ but large crystals (1000μ) without riming are frequently observed.

The studies at Climax indicate that accretional growth definitely plays a subordinate role to that of diffusional growth at that location. There is evidence that this may not be true in some of the warmer storms over the San Juan barrier. This is seen in Figure 5 where the mean daily snowfall on Wolf Creek Pass does not show an abrupt decrease at the warmer cloud top temperatures.

The fact that nature relies on accretion for the removal of cloud water does not necessarily mean this process should be utilized in an operational precipitation management program. In general we have the relationship

$$I_c = O_D + O_{Acc} + L \qquad (15)$$

where I_c is the input condensate formed in lifting the airmass over the mountain barrier, O_D is the precipitation output due to diffusional growth of ice crystals, O_{Acc} is the precipitation output due to accretion of cloud droplets to ice crystals, and L is the cloud water lost to precipitation through inefficient processes involving evaporation to the atmosphere.

The core of the problem is to reduce the loss (L) to a minimum. Whether the cloud water is brought to the ground by diffusional or accretional growth is of no importance in itself. However, there will be times when the naturally occurring accretion process has the capability of bringing more cloud water to the ground than if the precipitation process was converted entirely to one of diffusional growth.

The accretion process might help solve a particular targeting problem. The higher fall velocities of the rimed crystals might be utilized to optimize precipitation as near the upwind portion of the cloud as possible. This need might arise under conditions of very high wind speeds where many unrimed crystals might be carried over the mountain barrier without deposition.

Another case where the accretion process might be utilized is for a very warm cloud system (-5C to -10C cloud top) where the optimum number of ice crystals required would be so large, and present generators so inefficient, that the economic cost of the operation becomes disproportionately large.

In the majority of cases it appears wise to convert all the cloud water through the diffusional process whenever possible. Details of the accretional process are not well understood at this time, and the diffusion process is to be preferred whenever applicable.

h. The ballistics problem

The deposition of artificially produced ice crystals onto the mountain barrier depends upon the integrated time required for several complex processes to transpire. Initially, there is the transport time for artificial ice nuclei to travel from the generator site to the point of activation in the cloud system. There is the additional residence time that the ice crystal grows in the cloud system and lastly, the final settling time of the crystal from cloud base to the mountain.

The transport time for artificial ice nuclei to travel from the generator site to the point of activation in the cloud system is extremely difficult to determine. The problem is, of course, somewhat alleviated by airborne seeding. The vertical spread of the seeding material may be due to diffusion and convective transport aided by the dynamic and orographic components of the vertical motion field. Thus, stability and vertical wind shear considerations over the site play an important role.

The Pasquill-Gifford diffusion equation has been found to apply reasonably well in plume tests conducted in the Park Range (Bollay Assoc., 1968) for near neutral stability conditions. It is expected that solutions of the diffusion equations, plume studies from the given areas, and some wind tunnel test results will supply the information needed to evaluate the dispersal of seeding material to the cloud system and the transport time from generator site to activation.

The residence time of the ice crystal in the cloud system is a function of its activation level, growth rate and settling speed. The growth rate of ice crystals as a function of temperature is still not well established. Two of the more recent and comprehensive studies (Todd, 1964, and Fukuta and Wang, 1968) illustrate the need for further investigation into the complex subject.

Todd gathered information from tables, scatter diagrams, and micrographs and extracted crystal growth information. Ice crystal dimensions were then related to time of growth and it was found that the growth of the crystal axes (a and c) could be fitted to equations of the type:

$a = k_a t^\alpha$ and $c = k_c t^\beta$ where α and β are discrete functions of temperature, and k_a and k_c are continuous functions of temperature. Figure 6 shows the crystal mass 60 seconds after nucleation according to Todd. Also in Figure 6 is shown the crystal mass after 50 seconds according to the observations of Fukuta and Wang, and that computed from the diffusional growth equation. The ventilation and vapor factors are considered to equal one in the growth equation. It is seen that observed crystal growth rates are not well explained by the diffusional growth equation, especially those of Todd. All three curves, however, point to a maxima in the rate of growth in the temperature range from -15C to -18C.

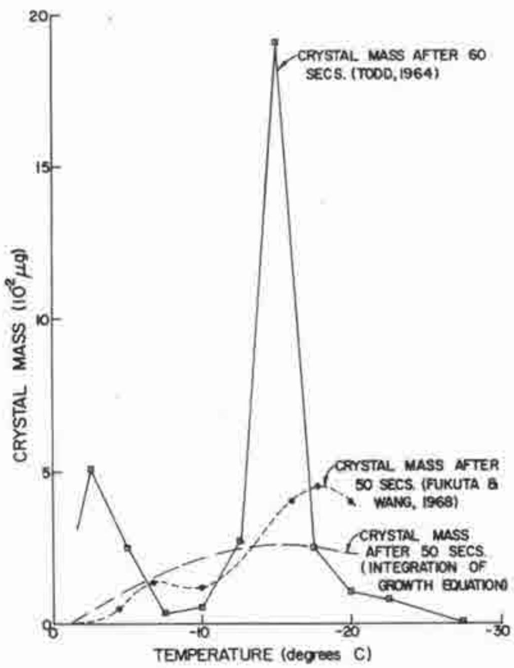


Figure 6. --Mass of a crystal after 50 to 60 seconds of growth as a function of environmental temperature.

Crystals growing and settling with respect to a saturated orographic stream will experience a varying temperature environment. Thus, the growth rate must be integrated with respect to temperature which further complicates its determination.

The settling speed of ice crystals is a function of their habit, amount of riming, and in some cases a function of their size. Figure 7 shows the observed terminal velocities of various crystal habits as determined by several investigators. Clearly, the agreement between investigators is not good and more experimental work is needed for better definition.

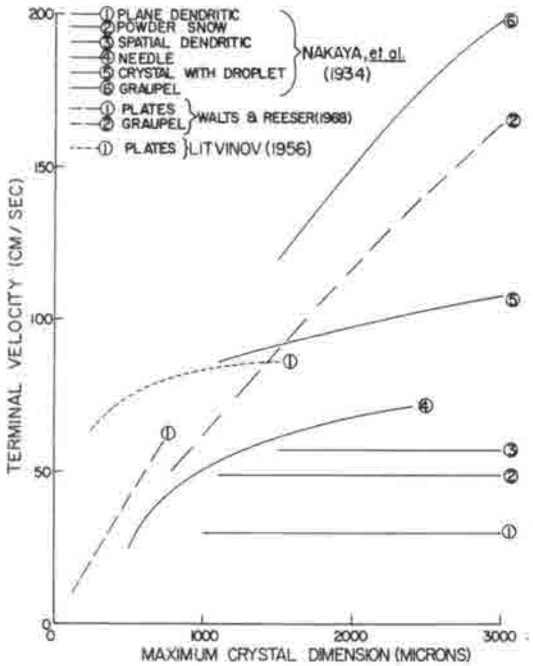


Figure 7. --Observed terminal velocities of various crystal habits as a function of crystal size.

It is evident that the information required to compute (1) the time to transport artificial ice nuclei from the generator site to point of activation in the cloud system, (2) the growth and residence period within the cloud system, and (3) the final settling time from cloud base to mountain, is fragmentary and inconclusive. Modelling of these processes will therefore by necessity be full of assumptions and approximations.

It appears that due to the many uncertainties embodied in computing generator-target separation distances that equal consideration should be given to experimental results. Thus, computed generator-target designs should be tempered with experimental designs that have yielded successful results.

B. Experimental basis for a pilot project and meteorological criteria for weather modification operations

The programs of weather modification research carried out in the central Colorado Rockies and the operational - type program carried out in the Wolf Creek Pass area by the State of Colorado provide the primary empirical type information being utilized for the design of the pilot program. This section of the report briefly discusses these programs and presents some of the results in a form that can be utilized in the design and operation of a pilot project.

1. Experimental Design

a. Climax experiment

The experimental design of the Climax experiment has been presented in detail elsewhere (Grant and Mielke, 1967), so only a brief synopsis is presented below.

Randomization is employed in obtaining the seeded and non-seeded samples. The randomization is restricted to the extent that large blocks (20 to 40) have the same number of seeded and non-seeded cases.

The sampling unit is a 24-hour interval of time.

Eight standard Weather Bureau stations located southwest, west, northwest and north of the experimental site are available for use as control stations.

The criteria of an experimental day is that at least .01 inches of precipitation be forecasted during a 24-hour sampling unit at Leadville, Colorado, accompanied by a 500 mb wind direction between 210 degrees and 360 degrees inclusive. This forecast is prepared by the United States Weather Bureau in Denver. The forecasters have no access to the seeding decision.

Generators are turned on $\frac{1}{2}$ to 1 hour prior to the beginning of the experimental day, and shut off $\frac{1}{2}$ to 1 hour prior to the end of the day depending upon their respective distances from the primary target area.

b. Wolf Creek experiment

The Wolf Creek Pass experiment is inherently an operational program whose basic purpose and objective was to augment snowfall over an area of the San Juan Mountain Massif centered at the summit of Wolf Creek Pass. In order to secure useful data from this operational program eight snowboards were installed over the pass. Recording precipitation gages were added such that hourly precipitation amounts are available near the summit and on the west and east sides of the pass. The experimental design of the Wolf Creek experiment is summarized below.

Randomization is employed in obtaining the seeded and non-seeded samples. The randomization is restricted to entire winter seasons. This resulted in the winter seasons of 1964-65 and 1966-67 being seeded periods while the winter seasons of 1965-66 and 1967-68 were left non-seeded.

The sampling unit is a 24-hour interval of time.

Seven standard Weather Bureau stations located south, southwest and west of the experimental site are available for use as control stations.

The criteria of an experimental day is that at least .01 inches of precipitation occurred during a 24-hour sampling unit at one or more of the recording precipitation gages on Wolf Creek Pass, or at the control station.

The generator operations were controlled by a private meteorological group from Denver (Water Resources Development Corp.) during the winter season of 1964-65, and by Colorado State University personnel during the winter season of 1967-68. An attempt was made to have the appropriate ground-based seeding generators running at all times when precipitation was occurring or was imminent.

2. Statistical Evaluation Procedures

Three statistical methods that evaluate differences in precipitation between seeded and non-seeded periods have been discussed by Grant and Mielke (1967) so only a brief synopsis is repeated here. The first two methods apply nonparametric procedures to all observations. The third method is based on a parametric technique introduced by Thom (1957).

The first nonparametric technique (NP1) employs a two-sample Wilcoxon test while the second nonparametric procedure (NP2) utilizes a two-sample sum of squared ranks test. The underlying assumption in both techniques is that if seeding has no effect on the amount of precipitation, then the target precipitation for seeded and non-seeded days represent observations from identical distributions. When analyzed with controls the assumption is that the difference between the control and target precipitation for seeded and non-seeded days represents observations from identical distributions.

The parametric approach (PAR) assumes that precipitation data may be approximated by a gamma distribution. The raw data is transformed into normalized data that is suitable for the application of a simple regression analysis. The basic information for both seeded and non-seeded periods consists of non-zero paired observations (target and control). The expectation of the resulting normalized test statistic is taken in terms of the assumed underlying gamma distributed variables. Then a point estimate of a scale change during the seeded period with respect to the non-seeded period can be obtained.

The utilization of three different methods to statistically evaluate the experimental data has certain advantages for interpreting results. The two-sample Wilcoxon test (NP1) gives equal emphasis to all observations while the two-sample sum of squared ranks test (NP2) places greater emphasis on the larger precipitation amounts. The nonparametric methods (NP1 and NP2) have the advantage of being applicable to all forms of data. However, the parametric method (PAR) is seriously deficient in being able to only cope with reduced data amounts involving days in which both target and control precipitation amounts are not zero.

Analysis of the Climax and Wolf Creek experiments is shown with and without the inclusion of control precipitation in the computations. The large variability in the experimental data combined with the relatively small sample sizes resulting from partitioning, make it impossible to derive tight confidence intervals of scale estimators. In order to supply some meaningful interpretation of the results, the probability of the scale change being exceeded in the same sense by chance (p-value) is included in the final tabulated summaries.

Results of three different and independent experimental samples are depicted in the summary tables of final results. Since the emphasis in this paper is on the distribution of seeding effects under specified meteorological criteria, a brief description of the composition of these three sets of independent data are given.

3. Basic Data

a. Climax I data sample (251 cases)

During the period 1960-65 there were 283 experimental days defined for the Climax experiment. Preliminary results of this entire sample were previously discussed (Grant and Mielke, 1967). Chappell (1967) in a further analysis of the 1960-65 Climax data found that several of the experimental events had wind directions that could not bring the seeding material toward the primary target area. If only those experimental events that have 500 mb wind directions between 210 degrees and 360 degrees inclusive are considered (as originally defined for the experiment), the sample reduces to 251 cases.

b. Climax II data sample (127 cases)

During the period 1965-68 there were 231 experimental days defined for the Climax experiment. Five of these events were also found to have 500 mb wind flows outside the prescribed direction interval, reducing the original sample to 226 cases. Further investigation indicated that on 99 other experimental days seeding from other activities close upstream (100 miles or less) could have affected either the primary target area or the control area. Therefore, there are only 127 "clean" experimental days available during this period for analysis with controls. The overall variations of seeding effects with 500 mb temperatures for the original samples composed of 231 experimental days (Grant, et al., 1969) is essentially duplicated by the "clean sample" comprised of 127 days.

c. Wolf Creek I data sample (362 cases)

There were 362 days that met the prescribed criteria for an experimental event at Wolf Creek Pass during the four winter seasons from 1964-68. It should be mentioned that in this total sample there are 59 designated seeded cases where actually no seeding was conducted. These 59 cases were heavily biased toward low precipitation amounts. They have been retained in the seeded group since there is no acceptable way to remove their counterpart from the non-seeded events. It is likely that seeding effects are being diluted by the retention of these 59 cases in the total sample.

The results shown for the samples at Climax are for two sensors located within a few feet of one another at the High Altitude Observatory of the University of Colorado, near the summit of Fremont Pass. Consideration of elevation and spatial variation of precipitation over a network of 65 stations does not substantially alter the results presented below (Mielke, et al., 1969). The results shown for the Wolf Creek I sample are based on precipitation amounts recorded near the summit of Wolf Creek Pass. This sensor is an 8 inch shielded recording type gage as is one of the sensors in the

Climax group. The other sensors in the Climax group are snowboards.

4. Pertinent Results from the Climax and Wolf Creek Pass Investigation

A preliminary analysis of the Climax experimental data from 1960-65 was reported by Grant and Mielke (1967). The original sample of 283 events indicated the average precipitation on seeded days was 54% greater than on corresponding non-seeded days for 500 mb temperatures of -20C and warmer. The average precipitation on seeded days was 12% more for 500 mb temperatures from -21C through -23C, but was 15% less when 500 mb temperatures ranged from -24C to -39C.

Chappell (1967) in a further analysis of the 1960-65 Climax data found that when only those events having 500 mb wind directions between 210 degrees and 360 degrees inclusive were included (as originally defined for the experiment), the precipitation on seeded days was estimated to exceed by 100% the non-seeded precipitation for 500 mb temperatures of -20C and warmer.

Further analysis of the 1960-65 Climax data is now completed and results from two other in independent samples (Climax II and Wolf Creek I) are available for comparison. The Climax I and Climax Climax II results are presented for identical meteorological stratifications. The stratifications used in presenting the Wolf Creek I results are quite similar but not necessarily identical to the Climax categories. This results from partitioning the Wolf Creek data independently.

The stratifications presented in the results are for meteorological variables which the model presented indicates are relevant for delineating modification potential. These parameters relate to vertical motion through orographic influences, stability and baroclinicity. Other variables measure the available moisture and the potential condensate in the air mass approaching the mountain barrier. The influence of the natural supply of effective ice nuclei is investigated through the 500 mb temperatures (near cloud top). Since the average number of ice nuclei activated increases by a factor of about ten for every 4C decrease in temperature, the coldest region where condensation is occurring (near cloud top) produces about 9/10 of the total ice crystals in the cloud system.

a. Cloud top temperatures (500 mb)

The distribution of seeding effects with 500 mb temperatures is shown in Table I. The trend of the seeding effect with temperature is striking and duplicated by all three independent samples. Several of the statistical tests for the warmest and coldest categories are significant at less than 5% level of confidence and a few at the 1% level. Even the relatively small Climax II sample shows such values of significance.

The results indicate that snowfall has been decreased near the mountain summit when seeding the very cold cloud systems. This result is to be expected from the model. Figure 3 indicates that when 500 mb temperatures are -28C and colder, there is present naturally 100 or more excess ice nuclei for the conditions estimated to be representative of the Climax and Wolf Creek Pass areas. Additional ice nuclei are not needed to maximize the precipitation process and would serve only to reduce the size of the growing crystals. Seeding these very cold cloud systems may be reducing the precipitation efficiency as the ice to water ratio in the cloud becomes too large. Part of the observed decrease may be due to the smaller crystals being carried more easily over the mountain summit, and in a few extremely cold cases the precipitation process may be halted by complete icing of the cloud system.

Snowfall increases are estimated to be from near 100% to over 200% by the various statistical methods when seeding the warmest 500 mb temperatures. This is consistent with the model which indicated natural ice nuclei was deficient at all 500 mb temperatures above -21C for estimated Climax and Wolf Creek Pass conditions.

It is interesting that the results in the intermediate 500 mb temperature category agree well with the model. The Climax samples show near zero change or slight decreases in snowfall when seeding events having 500 mb temperatures from -21C through -25C. The model indicates optimum ice nuclei concentrations are present in the Climax area at 500 mb temperatures from -21C to -23C. The snowfall increases observed at Wolf Creek Summit when seeding 500 mb temperature from -20C through -23C are also projected by the model since optimum ice nuclei concentrations appear at 500 mb temperatures from -23C to -25C for Wolf Creek Pass conditions.

The stronger orographic effect at Wolf Creek Pass extends the range of modification potential into colder cloud top temperatures. This is quite important since it is in this intermediate temperature range (-21C to -25C) that snowfall in the Colorado Rockies has its greatest frequency.

b. Moisture supply

The distribution of seeding effects with respect to parameters that measure various aspects of the moisture supplied to the mountain barrier are shown in Table II and Table III. The variation of seeding effects with the 700 mb mixing ratio is depicted in Table II. The moisture parameter shown in Table III is computed by lifting a 700 mb parcel to 500 mb by adiabatic and pseudo-adiabatic processes (above condensation level) and dividing the resultant condensate by the thickness of the saturated layer below 500 mbs.

Once again the agreement between the three independent samples is excellent. All show decreases in snowfall when the drier cases are seeded. Substantial snowfall increases are observed in all samples when seeding the most moist events. The intermediate stratifications indicate near zero change or slight increases for all samples. The snowfall decreases observed when seeding the lowest 700 mb mixing ratio category are seen to be significant at the 5% level for most tests in the Climax I

TABLE I. --Estimate of scale changes during seeded periods with respect to non-seeded periods as computed by three statistical methods. Scale changes are shown as a function of the 500 mb temperature.

Stratification (°C)	Total Sample Size	Sample Size Utilized	Method	With Controls Scale Change (%)	With Controls P-Value	Without Controls Scale Change (%)	Without Controls P-Value
Climax I							
-35 thru -26	S 32	S 32	NP1	-18	.109	-31	.0091
	NS 34	NS 34	NP2	-8	.316	-22	.0329
		(S28, NS34)	PAR	-23	.068		
-25 thru -21	S 53	S 53	NP1	-1	.472	-1	.492
	NS 56	NS 56	NP2	-13	.309	-5	.390
		(S43, NS43)	PAR	-7	.345		
-20 thru -11	S 35	S 35	NP1	+142	.041	+100	.076
	NS 41	NS 41	NP2	+89	.171	>+200	.024
		(S19, NS25)	PAR	+102	.0023		
Climax II							
-35 thru -26	S 18	S 18	NP1	-28	.261	-46	.0039
	NS 17	NS 17	NP2	-50	.152	-25	.0329
		(S15, NS17)	PAR	-38	.059		
-25 thru -21	S 23	S 23	NP1	-1	.492	+6	.390
	NS 32	NS 32	NP2	-30	.341	-1	.496
		(S20, NS26)	PAR	-5	.421		
-20 thru -11	S 20	S 20	NP1	>+200	.0301	>+200	.071
	NS 17	NS 17	NP2	+176	.149	>+200	.042
		(S14, NS10)	PAR	+146	.0102		
Wolf Creek Summit							
-35 thru -24	S 43	S 42	NP1	-15	.218	-15	.264
	NS 61	NS 61	NP2	-25	.071	-22	.164
		(S31, NS48)	PAR	-9	.302		
-23 thru -20	S 57	S 47	NP1	+49	.053	+22	.233
	NS 68	NS 66	NP2	+62	.044	+23	.192
		(S32, NS45)	PAR	+43	.0384		
-19 thru -11	S 64	S 58	NP1	+95	.068	>+200	.0037
	NS 69	NS 54	NP2	+200	.0207	>+200	.0125
		(S31, NS28)	PAR	+81	.0113		

sample. Both the moist and intermediate categories of the Wolf Creek I sample show snowfall increases when seeded that are significant at about the 5% level.

It appears that the vertical gradient of potential condensate computed for the 700-500 mb layer stratifies the seeding effects somewhat better. Snowfall decreases, when seeding cases in the driest category, are significant at the 1% for the Climax I sample and at the 5% level for the Climax II sample. All three samples indicate snowfall increases when seeding the more moist events. The two-sample sum of squared ranks test is significant at the 1% level for the Wolf Creek sample.

These results are consistent with the model presented. As the rate of cloud water supplied increases, the concentration of ice crystals needed to convert the cloud water to ice at the new rate also increases if other variables remain constant. The results in Table II and Table III indicate that cloud water is frequently supplied at a rate in the Climax and Wolf Creek Pass areas, that is in excess of the natural capacity of the cloud system to convert to ice form. The effect of seeding under these conditions should be to increase the rate at which the cloud water may be extracted resulting in more snowfall on the mountain barrier.

The equivalent potential temperature evaluated near or just below cloud base identifies the pseudoadiabatic process curve of rising cloud parcels. It combines the moisture and temperature characteristics of the air mass approaching the mountain barrier into a single parameter. Table IV shows the distribution of seeding effects as a function of the 700 mb equivalent potential temperature.

TABLE II. --Estimate of scale changes during seeded periods with respect to non-seeded periods as computed by three statistical methods. Scale changes are shown as a function of the 700 mb mixing ratio.

Stratification (GM/KGM)	Total Sample Size	Sample Size Utilized	Method	With Controls Scale Change (%)	With Controls P-Value	Without Controls Scale Change (%)	Without Controls P-Value
Climax I							
0.4 to < 1.3	S 27	S 27	NP1	-28	.171	< -50	.0392
	NS 25	NS 25	NP2	< -50	.041	< -50	.0125
		(S17, NS19)	PAR	-34	.115		
1.3 to < 2.8	S 72	S 72	NP1	+7	.305	+13	.261
	NS 89	NS 89	NP2	+10	.258	+19	.147
		(S56, NS70)	PAR	+14	.166		
2.8 to < 4.6	S 21	S 21	NP1	+65	.071	+90	.138
	NS 17	NS 17	NP2	+132	.255	+92	.206
		(S17, NS13)	PAR	+35	.201		
Climax II							
0.4 to < 1.3	S 14	S 14	NP1	-32	.291	-22	.264
	NS 11	NS 11	NP2	<-50	.074	<-50	.108
		(S8, NS8)	PAR	-52	.171		
1.3 to < 2.8	S 36	S 36	NP1	+23	.187	+14	.298
	NS 46	NS 46	NP2	-6	.409	+23	.138
		(S31, NS39)	PAR	+16	.224		
2.8 to < 4.6	S 11	S 11	NP1	+25	.181	+180	.152
	NS 9	NS 9	NP2	+164	.106	+118	.305
		(S10, NS6)	PAR	+13	.421		
Wolf Creek Summit							
0.5 to < 1.9	S 69	S 64	NP1	-2	.480	-10	.409
	NS 82	NS 79	NP2	-13	.323	-12	.334
		(S34, NS45)	PAR	-9	.337		
1.9 to < 2.8	S 59	S 50	NP1	+45	.050	+48	.111
	NS 76	NS 74	NP2	+66	.0197	+41	.113
		(S33, NS51)	PAR	+58	.0040		
2.8 to < 5.2	S 36	S 33	NP1	+57	.117	+165	.0183
	NS 40	NS 28	NP2	+64	.127	+111	.053
		(S27, NS25)	PAR	+54	.054		

Again the consistency of the three independent samples is apparent. Decreases in snowfall are noted when seeding the colder equivalent potential temperatures. At warmer equivalent potential temperatures the seeding effect reverses and snowfall increases when seeding the warmest stratifications are substantial. These increases are significant at the 5% level for most tests in the Climax I and Wolf Creek I samples. Both the two-sample Wilcoxon test and the two-sample sum of squared ranks test indicate significance at the 1% level for the Wolf Creek I sample when analyzed without control.

c. Stability and baroclinic considerations

The stability of the air mass approaching the mountain barrier may influence the modification potential in complex ways. If the air mass is convectively unstable precipitation may tend to concentrate in relatively small cells and convective lines. The stronger upward motions in these cells and lines would result in high supply rates of cloud water in localized areas. However, the stronger upward motions would also probably result in higher cloud tops. Since the number of effective ice nuclei increases exponentially with cloud top height, while the need for additional ice nuclei grows only directly with the upward speed, it is not obvious that modification potential would be greater in unstable air masses. On the other hand, if the convective stability is quite low (near zero) and modification potential exists for other reasons (lack of available ice nuclei for existing cloud conditions), the additional release of latent heat resulting from seeding might generate precipitation of a convective nature that would not otherwise have occurred.

The static stability of the air mass also affects the nature of the laminar flow over the

TABLE III. --Estimate of scale changes during seeded periods with respect to non-seeded periods as computed by three statistical methods. Scale changes are shown as a function of a computed vertical gradient of potential condensate in the 700-500 mb layer.

Stratification GM/(KGM)(100 mb)	Total Sample Size	Sample Size Utilized	Method	With Controls Scale Change (%)	With Controls P-Value	Without Controls Scale Change (%)	Without Controls P-Value
Climax I							
0 to <0.7	S 24	S 24	NP1	-36	.058	< -50	.0045
	NS 21	NS 21	NP2	-46	.0314	< -50	.0071
		(S17, NS19)	PAR	-40	.072		
0.7 to <1.3	S 76	S 76	NP1	+4	.371	+11	.284
	NS 86	NS 86	NP2	+6	.334	+8	.274
		(S61, NS66)	PAR	+3	.401		
1.3 to <2.0	S 20	S 20	NP1	+117	.0351	+53	.154
	NS 24	NS 24	NP2	+171	.147	+100	.145
		(S12, NS17)	PAR	+128	.0150		
Climax II							
0 to <0.7	S 15	S 15	NP1	-38	.147	< -50	.049
	NS 12	NS 12	NP2	<-50	.0239	< -50	.0336
		(S10, NS11)	PAR	-45	.134		
0.7 to <1.3	S 36	S 36	NP1	+7	.341	+ 5	.397
	NS 42	NS 42	NP2	-5	.452	+16	.212
		(S31, NS34)	PAR	+2	.468		
1.3 to <2.0	S 10	S 10	NP1	>+200	.0239	>+200	.0392
	NS 12	NS 12	NP2	>+200	.082	>+200	.142
		(S8, NS8)	PAR	+145	.090		
Wolf Creek Summit							
0 to <0.8	S 33	S 30	NP1	-21	.184	-20	.187
	NS 38	NS 34	NP2	-39	.074	-24	.102
		(S18, NS25)	PAR	-18	.239		
0.8 to <1.2	S 58	S 55	NP1	+11	.394	-14	.370
	NS 81	NS 80	NP2	+2	.448	-15	.284
		(S36, NS53)	PAR	+20	.149		
1.2 to <2.0	S 73	S 62	NP1	+128	.0202	>+200	.0025
	NS 79	NS 67	NP2	>+200	.0021	>+200	.0012
		(S40, NS43)	PAR	+65	.0094		

mountain barrier. This is apparent from the influence the static stability term exerts in the wave equations for flow over mountain barriers as discussed by Scorer (1953). Thus, the static stability helps to determine the orographically induced vertical motion field over the mountain barrier. The integrated effect of stability upon modification potential is therefore difficult to assess.

The distribution of seeding effects with a convective stability index is shown in Table V. The three independent samples are in agreement in most respects. All three samples indicate snowfall decreases when seeding the most stable categories. The two Climax samples show snowfall increases when seeding the most unstable events (less than 1.0) and again in an intermediate range (4.0 to 8.0). This double mode in evidence at Climax is not repeated at Wolf Creek Summit, but instead a gradual decrease in positive seeding effects with increasing stability is noted. The increase in snowfall when seeding the unstable events is significant at the 5% level for some of the tests for Climax I and Wolf Creek I samples.

The mean temperature advection in the 700-500 mb layer has been computed and provides a measure of the baroclinic state of the atmosphere. The distribution of seeding effects with the mean temperature advection in the cloud layer is shown in Table VI. The three samples are again quite consistent. It is seen that snowfall increases are observed when seeding the moderate baroclinic conditions (warm or cold advection). The snowfall increases at Climax are spectacular when seeding the moderate warm advection events. All tests indicate significance at the 5% level in the Climax I sample.

TABLE IV. --Estimate of scale changes during seeded periods with respect to non-seeded periods as computed by three statistical methods. Scale changes are shown as a function of the 700 mb equivalent potential temperature.

Stratification (°K)	Total Sample Size	Sample Size Utilized	Method	With Controls Scale Change (%)	With Controls P-Value	Without Controls Scale Change (%)	Without Controls P-Value
Climax I							
281.0 to < 294.7	S 23	S 23	NP1	-31	.074	-27	.079
	NS 22	NS 22	NP2	-7	.345	-22	.074
		(S20, NS21)	PAR	-29	.123		
294.7 to < 305.7	S 61	S 61	NP1	-3	.413	-18	.156
	NS 64	NS 64	NP2	-24	.123	-12	.227
		(S46, NS50)	PAR	-1	.476		
305.7 to < 325.7	S 36	S 36	NP1	+95	.040	+108	.054
	NS 45	NS 45	NP2	+78	.089	+120	.047
		(S26, NS31)	PAR	+64	.0166		
Climax II							
281.0 to < 294.7	S 14	S 14	NP1	-32	.134	-17	.164
	NS 12	NS 12	NP2	-16	.264	-18	.081
		(S11, NS11)	PAR	-40	.142		
294.7 to < 305.7	S 28	S 28	NP1	+7	.371	-5	.401
	NS 34	NS 34	NP2	-50	.169	-1	.484
		(S23, NS27)	PAR	-3	.440		
305.7 to < 325.7	S 19	S 19	NP1	+130	.089	+95	.203
	NS 20	NS 20	NP2	+66	.174	+112	.102
		(S15, NS15)	PAR	+59	.106		
Wolf Creek Pass							
285.0 to < 297.6	S 30	S 30	NP1	-28	.100	-30	.145
	NS 42	NS 41	NP2	-39	.042	-32	.099
		(S19, NS32)	PAR	-22	.164		
297.6 to < 304.6	S 36	S 33	NP1	+23	.206	+6	.409
	NS 53	NS 53	NP2	+11	.305	+7	.386
		(S21, NS34)	PAR	+37	.085		
304.6 to < 309.6	S 47	S 40	NP1	+24	.166	+34	.154
	NS 51	NS 49	NP2	+36	.136	+28	.212
		(S23, NS26)	PAR	+33	.134		
309.6 to < 325.6	S 51	S 44	NP1	+139	.0329	>+200	.0019
	NS 52	NS 38	NP2	>+200	.0146	>+200	.0048
		(S31, NS29)	PAR				

Snowfall decreases appear in all three samples when seeding the strong baroclinic conditions. This is thought to result from extremely high wind speeds that exist during many of these events and this possibility will be discussed further when orographic influences are considered. When near barotropic conditions are seeded at Climax, little effect or slight decreases are observed. Only small snowfall increases are noted at Wolf Creek Summit for the same conditions.

d. Orographic effects

The orientation of the mountain barrier with respect to the air flow will have important bearing on the upward speed imparted to the air crossing the mountain barrier. This in turn, is vital to determining the rate at which cloud water is supplied in the cloud system. It would be expected that the larger supply rates would exist in flows nearly normal to the mountain massif. Since the Continental Divide runs east to west in the Climax area and southeast to northwest in the Wolf Creek Pass area, one would expect that seeding effects might be distributed differently with wind direction at the two sites.

Table VII and Table VIII show seeding effects distributed with the 700 mb wind direction and the 500 mb wind direction respectively. At Climax it is noted that snowfall increases result mainly from seeding the north-northwest and south-southwest wind

TABLE V. --Estimate of scale changes during seeded periods with respect to non-seeded periods as computed by three statistical methods. Scale changes are shown as a function of the convective stability in the 700-500 mb layer ($\theta_{E500} - \theta_{E700}$).

Stratification (°C)	Total Sample Size	Sample Size Utilized	Method	With Controls Scale Change (%)	With Controls P-Value	Without Controls Scale Change (%)	Without Controls P-Value
Climax I							
-3.0 to <+1.0	S 17	S 17	NP1	+60	.087	+128	.0359
	NS 23	NS 23	NP2	+33	.192	+91	.043
		(S16, NS18)	PAR	+19	.233		
1.0 to >4.0	S 36	S 36	NP1	-10	.334	-24	.171
	NS 38	NS 38	NP2	+3	.421	-14	.274
		(S25, NS29)	PAR	-5	.417		
4.0 to >8.0	S 42	S 42	NP1	+34	.142	+39	.166
	NS 40	NS 40	NP2	+12	.312	+32	.147
		(S33, NS31)	PAR	+38	.075		
8.0 to >19.0	S 25	S 25	NP1	-34	.312	<-50	.047
	NS 29	NS 29	NP2	<-50	.192	-38	.099
		(S16, NS23)	PAR	-26	.161		
Climax II							
-3.0 to <+1.0	S 8	S 8	NP1	+5	.316	+68	.169
	NS 14	NS 14	NP2	+7	.341	+26	.189
		(S8, NS11)	PAR	-6	.425		
1.0 to <4.0	S 16	S 16	NP1	+3	.421	-30	.161
	NS 19	NS 19	NP2	-5	.472	-2	.496
		(S11, NS15)	PAR	+12	.378		
4.0 to <8.0	S 25	S 25	NP1	+45	.117	+126	.074
	NS 19	NS 19	NP2	+21	.242	+77	.100
		(S23, NS16)	PAR	+33	.171		
8.0 to <19.0	S 12	S 12	NP1	+3	.448	<-50	.145
	NS 14	NS 14	NP2	<-50	.084	<-50	.195
		(S7, NS11)	PAR	-36	.201		
Wolf Creek Summit							
-3.5 to <+0.5	S 19	S 16	NP1	+40	.221	+95	.075
	NS 14	NS 12	NP2	+98	.078	+112	.040
		(S14, NS11)	PAR	+63	.063		
0.5 to <4.5	S 65	S 56	NP1	+49	.054	+59	.067
	NS 86	NS 81	NP2	+37	.078	+49	.071
		(S40, NS63)	PAR	+31	.059		
4.5 to <8.5	S 52	S 48	NP1	+41	.076	+46	.097
	NS 72	NS 67	NP2	+41	.095	+31	.121
		(S29, NS35)	PAR	+60	.0066		
8.5 to <17.0	S 28	S 27	NP1	-4	.413	-7	.425
	NS 25	NS 20	NP2	-50	.378	-41	.166
		(S11, NS12)	PAR	+3	.480		

flows. This is probably due to the east-west orientation of the Continental Divide through this area. At Wolf Creek Summit large snowfall increases are observed when seeding the southwesterly and west-southwesterly flows. For 700 mb wind directions from 230 degrees through 250 degrees, snowfall increases of over 100% are realized at Wolf Creek Summit with all tests indicating significance at the 1% level.

When seeding the westerly wind flows at Climax, little change in precipitation is affected. Thus, modification potential appears significantly related to orographic influences through the rate at which cloud water is supplied in the cloud system by the forced lifting over the mountain barrier.

TABLE VI. --Estimate of scale changes during seeded periods with respect to non-seeded periods as computed by three statistical methods. Scale changes are shown as a function of a computed mean temperature advection in the 700-500 mb layer.

Stratification (C/12 hr)	Total Sample Size	Sample Size Utilized	Method	With Controls Scale Change (%)	With Controls P-Value	Without Controls Scale Change (%)	Without Controls P-Value
Climax I							
1.4 to < 4.4	S 25	S 25	NP1	>+200	.0031	>+200	.0044
	NS 31	NS 31	NP2	+119	.047	>+200	.0119
		(S19, NS22)	PAR	+98	.0150		
-1.6 to <+1.4	S 50	S 50	NP1	-18	.159	-48	.0150
	NS 55	NS 55	NP2	-16	.159	-28	.085
		(S34, NS43)	PAR	-13	.215		
-3.6 to < -1.6	S 17	S 17	NP1	+67	.149	+73	.154
	NS 21	NS 21	NP2	+68	.179	+42	.206
		(S15, NS15)	PAR	+24	.201		
4.4 to < 14.0 and -12.0 to < -3.6	S 28 NS 24	S 28	NP1	-28	.082	-36	.056
		NS 24	NP2	-17	.169	-29	.064
		(S22, NS22)	PAR	-24	.109		
Climax II							
1.4 to < 4.4	S 13	S 13	NP1	>+200	.100	>+200	.051
	NS 15	NS 15	NP2	>+200	.159	>+200	.066
		(S11, NS11)	PAR	+75	.159		
-1.6 to <+1.4	S 26	S 26	NP1	+11	.305	-27	.215
	NS 27	NS 27	NP2	-37	.261	-9	.382
		(S19, NS22)	PAR	+10	.367		
-3.6 to < -1.6	S 10	S 10	NP1	+20	.288	+80	.169
	NS 13	NS 13	NP2	+130	.082	+190	.0367
		(S9, NS9)	PAR	+14	.330		
4.4 to < 14.0 and -12.0 to < -3.6	S 12 NS 11	S 12	NP1	-32	.087	-37	.0281
		NS 11	NP2	< -50	.0322	-31	.057
		(S10, NS11)	PAR	-37	.048		
Wolf Creek Summit							
0.4 to < 5.4	S 51	S 45	NP1	+48	.121	+23	.261
	NS 69	NS 60	NP2	+49	.142	+39	.192
		(S24, NS36)	PAR	+62	.0197		
-0.6 to <+0.4	S 54	S 48	NP1	-10	.401	+23	.245
	NS 65	NS 60	NP2	+24	.212	+33	.147
		(S26, NS37)	PAR	+19	.233		
-3.6 to < -0.6	S 47	S 42	NP1	+56	.0294	+63	.0495
	NS 54	NS 53	NP2	+37	.064	+49	.0485
		(S34, NS40)	PAR	+55	.0045		
5.4 to < 10.0 and -10.0 to < -3.6	S 12 NS 10	S 12	NP1	-5	.319	< -50	.095
		NS 8	NP2	< -50	.218	< -50	.075
		(S10, NS8)	PAR	+8	.421		

It might be expected that modification potential would increase with the speed of the horizontal wind flow since higher upward speeds would be induced if the flow was near normal to the mountain barrier. However, whether this potential is realized in increased snowfall on top the mountain is also dependent upon the total time it takes for (1) the artificial nuclei to reach and activate in the cloud system, (2) the crystal to grow, and (3) the crystal to settle to the mountain. Thus, the generator-target spacing and the horizontal extent of the orographic cloud itself become important considerations in whether the existing modification potential is realized at the top of the mountain. The interaction between the ice nuclei concentration and crystal size becomes increasingly important when seeding the very high

TABLE VII. --Estimate of scale changes during seeded periods with respect to non-seeded periods as computed by three statistical methods. Scale changes are shown as a function of the 700 mb wind direction.

Stratification (Degrees)	Total Sample Size	Sample Size Utilized	Method	With Controls Scale Change (%)	With Controls P-Value	Without Controls Scale Change (%)	Without Controls P-Value
Climax I							
210 thru 240	S 14	S 14	NP1	>+200	.062	>+200	.071
	NS 16	NS 16	NP2	+37	.239	+159	.109
		(S9, NS9)	PAR	+100	.079		
250 thru 300	S 63	S 63	NP1	-6	.367	-29	.090
	NS 73	NS 73	NP2	+2	.429	-23	.142
		(S43, NS59)	PAR	+4	.397		
310 thru 350	S 25	S 25	NP1	+64	.099	+24	.251
	NS 26	NS 26	NP2	+20	.323	+22	.215
		(S23, NS22)	PAR	+23	.212		
0 thru 200	S 18	S 18	NP1	-46	.087	-3	.352
	NS 16	NS 16	NP2	-31	.108	0	.496
		(S15, NS12)	PAR	-25	.176		
Climax II							
210 thru 240	S 6	S 6	NP1	+30	.258	---	---
	NS 6	NS 6	NP2	+6	.488	---	---
		(S4, NS4)	PAR	+151	.097		
250 thru 300	S 32	S 32	NP1	+5	.390	-15	.261
	NS 35	NS 35	NP2	+2	.436	-4	.352
		(S24, NS29)	PAR	+5	.429		
310 thru 350	S 13	S 13	NP1	+45	.195	+15	.309
	NS 16	NS 16	NP2	-29	.330	+6	.334
		(S11, NS14)	PAR	+27	.236		
0 thru 200	S 10	S 10	NP1	-4	.421	---	---
	NS 9	NS 9	NP2	-1	.448	---	---
		(S10, NS6)	PAR	+1	.492		
Wolf Creek Summit							
220 thru 270	S 74	S 63	NP1	+60	.0129	+79	.0099
	NS 91	NS 81	NP2	+79	.0027	+84	.0035
		(S45, NS59)	PAR	+60	.0019		
230 thru 250	S 44	S 39	NP1	+109	.0071	+146	.0036
	NS 45	NS 38	NP2	+141	.0024	+164	.0006
		(S28, NS28)	PAR	+129	.0001		
260 thru 360 and	S 120	S 108	NP1	+10	.295	+15	.274
0 thru 220	NS 153	NS 143	NP2	+8	.337	-4	.460
		(S67, NS92)	PAR	+13	.212		

wind speeds, since the boundary condition may be reached where crystals start escaping over the mountain barrier that would have naturally fallen on the mountain summit.

Table IX and Table X show the distribution of seeding effects with respect to the 700 mb and 500 mb wind speeds, respectively. Table IX indicates decreases in snowfall for all three samples when seeding the highest 700 mb wind speed categories. The snowfall decreases are significant at the 5% level for most tests at Wolf Creek Summit. The seeding effect is near zero or slightly negative when seeding events in the lowest 700 mb wind speed category. These events would have low supply rates of cloud water due to the small orographic effect and usually there would be sufficient natural ice nuclei to convert the cloud water to ice form.

There is an irregular increase in positive seeding effects as the 700 mb wind speed increases toward the highest category. Snowfall increases of about 100% are observed in the Climax I sample when events having 700 mb wind speeds from 12 mps through 15 mps are seeded. Some of the tests indicate these increases to be significant at the 5% level. In the Wolf Creek I sample snowfall in increases of over 100% are indicated when seeding

TABLE VIII. --Estimate of scale changes during seeded periods with respect to non-seeded periods as computed by three statistical methods. Scale changes are shown as a function of the 500 mb wind direction.

Stratification (Degrees)	Total Sample Size	Sample Size Utilized	Method	With Controls Scale Change (%)	With Controls P-Value	Without Controls Scale Change (%)	Without Controls P-Value
Climax I							
210 thru 230	S 15	S 15	NP1	+68	.248	>+200	.0344
	NS 17	NS 17	NP2	+33	.397	+144	.166
		(S12, NS9)	PAR	+12	.405		
240 thru 270	S 47	S 47	NP1	0	.496	+5	.409
	NS 38	NS 38	NP2	+29	.138	+16	.316
		(S33, NS28)	PAR	+13	.255		
280 thru 300	S 34	S 34	NP1	-12	.221	-33	.075
	NS 33	NS 33	NP2	-8	.302	-32	.059
		(S27, NS28)	PAR	-20	.117		
310 thru 360	S 24	S 24	NP1	+58	.093	-7	.448
	NS 43	NS 43	NP2	+9	.359	+2	.394
		(S18, NS37)	PAR	+42	.102		
Climax II							
210 thru 230	S 7	S 7	NP1	-9	.386	---	---
	NS 8	NS 8	NP2	+53	.330	---	---
		(S5, NS5)	PAR	+49	.337		
240 thru 270	S 22	S 22	NP1	+27	.075	+174	.0268
	NS 18	NS 18	NP2	+56	.072	+98	.049
		(S19, NS12)	PAR	+14	.251		
280 thru 300	S 19	S 19	NP1	-18	.176	-34	.0274
	NS 13	NS 13	NP2	-31	.142	-12	.115
		(S16, NS12)	PAR	-32	.111		
310 thru 360	S 13	S 13	NP1	+48	.166	-20	.352
	NS 27	NS 27	NP2	-23	.421	-11	.452
		(S9, NS24)	PAR	+56	.136		
Wolf Creek Summit							
220 thru 240	S 41	S 36	NP1	+23	.152	+16	.245
	NS 50	NS 47	NP2	+13	.212	+17	.212
		(S29, NS42)	PAR	+60			
250 thru 280	S 61	S 55	NP1	+46	.056	+60	.043
	NS 69	NS 60	NP2	+69	.0146	+66	.0202
		(S37, NS45)	PAR	+77	.0046		
290 thru 360 and	S 62	S 56	NP1	+10	.386	+27	.221
0 thru 210	NS 79	NS 74	NP2	+13	.323	+5	.421
		(S28, NS34)	PAR	+18	.255		

events having 700 mb wind speeds from 11 mps through 16 mps. All tests indicate these snowfall increases to be significant at the 3% level, with most tests indicating significance near the 1% level. The distribution of seeding effects with the 700 mb wind speed for the Climax samples suggest a double mode with snowfall increases observed when seeding events having speeds from 6 mps to 7 mps and again from 12 mps to 15 mps. This double mode is even more apparent when seeding effects are distributed with the 500 mb wind speed (Table X). Snowfall increases are observed for events having 500 mb wind speeds from 12 mps through 16 mps and again from 22 mps through 27 mps. For the Climax I sample all tests indicate the snowfall increases of near 100% to over 200% are significant at about the 2% level, when seeding events having 500 mb wind speeds from 22 mps through 27 mps. Some of the tests also indicate that the snowfall increases observed when seeding events having 500 mb wind speeds from 12 mps through 16 mps are significant at the 1% level. Thus, significance is indicated by at least some tests for both wind speed modes. The existence of this double mode at Climax has been discussed previously by Chappell (1967) and is thought to relate to generator-target spacings embodied in the experimental design.

TABLE IX. --Estimate of scale changes during seeded periods with respect to non-seeded periods as computed by three statistical methods. Scale changes are shown as a function of the 700 mb wind speed.

Stratification (MPS)	Total Sample Size	Sample Size Utilized	Method	With Controls Scale Change (%)	With Controls P-Value	Without Controls Scale Change (%)	Without Controls P-Value
Climax I							
0 thru 5	S 17	S 17	NP1	-37	.131	+3	.405
	NS 21	NS 21	NP2	-42	.209	-1	.476
		(S15, NS16)	PAR	-14	.345		
6 thru 7	S 22	S 22	NP1	+19	.230	+4	.375
	NS 33	NS 33	NP2	+85	.056	+14	.312
		(S16, NS24)	PAR	+45	.085		
8 thru 11	S 55	S 55	NP1	+4	.409	-23	.134
	NS 40	NS 40	NP2	-5	.345	-5	.319
		(S40, NS32)	PAR	+1	.484		
12 thru 15	S 18	S 18	NP1	+115	.0281	+81	.136
	NS 26	NS 26	NP2	+137	.0281	+86	.131
		(S12, NS20)	PAR	+53	.069		
16 thru 27	S 8	S 8	NP1	-25	.152	-21	.371
	NS 11	NS 11	NP2	-25	.140	-11	.394
		(S7, NS10)	PAR	-33	.055		
Climax II							
0 thru 5	S 11	S 11	NP1	-26	.074	---	---
	NS 8	NS 8	NP2	+30	.326	---	---
		(S9, NS7)	PAR	-10	.417		
6 thru 7	S 9	S 9	NP1	+40	.169	-27	.312
	NS 19	NS 19	NP2	+2	.386	-22	.345
		(S6, NS15)	PAR	+48	.192		
8 thru 11	S 28	S 28	NP1	+33	.209	+5	.409
	NS 26	NS 26	NP2	+2	.468	+9	.323
		(S23, NS20)	PAR	+13	.330		
12 thru 15	S 9	S 9	NP1	+50	.227	---	---
	NS 9	NS 9	NP2	+126	.302	---	---
		(S7, NS7)	PAR	-12	.421		
16 thru 27	S 4	S 4	NP1	<-50	.125	---	---
	NS 4	NS 4	NP2	<-50	.129	---	---
		(S4, NS4)	PAR	-55	.184		
Wolf Creek Summit							
0 thru 10	S 108	S 94	NP1	-3	.456	-7	.405
	NS 142	NS 136	NP2	0	.416	-11	.309
		(S53, NS90)	PAR	+28	.043		
11 thru 16	S 40	S 33	NP1	+102	.0107	+150	.0039
	NS 49	NS 41	NP2	+140	.0104	+134	.0102
		(S25, NS28)	PAR	+52	.0322		
17 thru 28	S 16	S 16	NP1	-23	.045	-25	.157
	NS 7	NS 5	NP2	-21	.0268	-21	.0367
		(S12, NS4)	PAR	-53	.0158		

The Climax II sample also indicates this double mode and the observed increases in snowfall are significant at about the 3% level of confidence.

Snowfall increases of over 50% are observed at Wolf Creek Summit when seeding events having 500 mb wind speeds from 14 mps through 21 mps. These increases are indicated to be significant at about the 3% level for some tests, with the parametric test showing significance at the 1% level of confidence.

TABLE X. --Estimate of scale changes during seeded periods with respect to non-seeded periods as computed by three statistical methods. Scale changes are shown as a function of 500 mb wind speed.

Stratification (MPS)	Total Sample Size	Sample Size Utilized	Method	With Controls Scale Change (%)	With Controls P-Value	Without Controls Scale Change (%)	Without Controls P-Value
Climax I							
0 thru 11	S 25	S 25	NP1	-24	.215	+16	.345
	NS 27	NS 27	NP2	-28	.255	0	.496
		(S22, NS20)	PAR	-27	.125		
12 thru 16	S 27	S 27	NP1	+114	.0071	+49	.198
	NS 21	NS 21	NP2	+88	.142	+20	.319
		(S19, NS16)	PAR	+76	.0054		
17 thru 21	S 28	S 28	NP1	-17	.218	<-50	.0268
	NS 28	NS 28	NP2	-4	.405	-38	.075
		(S17, NS23)	PAR	+4	.448		
22 thru 27	S 26	S 26	NP1	+192	.0154	>+200	.0068
	NS 25	NS 25	NP2	+110	.0222	>+200	.0087
		(S22, NS18)	PAR	+64	.0222		
28 thru 43	S 14	S 14	NP1	-31	.236	-40	.218
	NS 30	NS 30	NP2	-47	.113	-39	.198
		(S10, NS25)	PAR	-9	.363		
Climax II							
0 thru 11	S 15	S 15	NP1	-18	.345	-2	.464
	NS 17	NS 17	NP2	-50	.268	+4	.394
		(S13, NS13)	PAR	-12	.367		
12 thru 16	S 16	S 16	NP1	+95	.0239	+9	.405
	NS 13	NS 13	NP2	+116	.323	+53	.203
		(S12, NS11)	PAR	+79	.0256		
17 thru 21	S 9	S 9	NP1	-17	.284	<-50	.078
	NS 12	NS 12	NP2	+4	.371	-20	.209
		(S6, NS11)	PAR	-9	.425		
22 thru 27	S 12	S 12	NP1	+198	.064	>+200	.0384
	NS 13	NS 13	NP2	+37	.159	>+200	.0197
		(S10, NS9)	PAR	+53	.156		
28 thru 43	S 9	S 9	NP1	-20	.298	-32	.171
	NS 11	NS 11	NP2	<-50	.129	-32	.171
		(S8, NS9)	PAR	-38	.125		
Wolf Creek Summit							
0 thru 13	S 43	S 35	NP1	-7	.436	+17	.298
	NS 66	NS 61	NP2	+21	.209	+33	.169
		(S21, NS35)	PAR	-3	.444		
14 thru 21	S 65	S 59	NP1	+53	.0329	+42	.102
	NS 84	NS 83	NP2	+65	.0170	+41	.071
		(S38, NS60)	PAR	+82	.0002		
22 thru 27	S 38	S 36	NP1	-9	.302	-30	.140
	NS 24	NS 21	NP2	-13	.278	-19	.187
		(S20, NS14)	PAR	+4	.440		
28 thru 42	S 18	S 17	NP1	+41	.198	+64	.156
	NS 24	NS 16	NP2	+17	.367	+37	.284
		(S15, NS12)	PAR	+47	.050		

The orographic effect upon the modification potential is demonstrated by the observed increases in snowfall when seeding those flows nearly normal to the mountain barrier. Also, positive seeding effects are observed to increase irregularly with the speed of the horizontal flow except at the highest wind speeds where snowfall decreases are generally observed again.

5. Discussion

The following observations are consistent with current cloud physics theory.

The largest snowfall increases are realized at cloud top temperatures where the greatest deficiency of effective ice nuclei is observed. No snowfall increases are observed where measurements indicate effective ice nuclei are normally plentiful.

The largest snowfall increases are observed when the wind flow and topographic features combine to produce an orographic stream having strong upward motions.

The largest snowfall increases are observed for events having the largest moisture supply.

Snowfall decreases are observed for the coldest and driest events, and the lowest wind speeds. These are the events that would have low supply rates of cloud water and normally excessive concentrations of effective ice nuclei.

Snowfall increases are observed at somewhat colder cloud top temperatures in the area having stronger upward speeds on the average.

Snowfall increases are observed when a moderate baroclinic zone is present in the 700 mb to 500 mb layer.

Two observations appear at first glance to be somewhat contradictory to the presented theory; the decreases in snowfall observed at the higher wind speeds and for the very strong baroclinic conditions. At this point one can only speculate on these findings. The very strong baroclinic events may be accompanied by higher than usual cloud tops as the strong baroclinicity probably reflects a stronger than normal synoptic disturbance. Under these conditions cloud tops may extend a few thousand feet above the 500 mb level and consequently, cloud top temperatures would be considerably colder than indicated by the 500 mb temperatures. Thus, effective ice nuclei might be naturally plentiful in these cloud systems. Since the extremely high wind speeds would normally accompany these intense baroclinic disturbances one could invoke this same argument to explain the decreases at high wind speeds. If one interprets the seeding effect at these high wind speeds as not really a decrease, but rather that it represents no effect another argument is possible. It can then be argued that the artificial nuclei do not have time to reach the cloud system, activate and grow to sufficient size to settle at the mountain summit, but rather are carried over the barrier. This infers a greater target-generator spacing should be employed during the high wind speed events than is available in the present design. If these decreases in snowfall are accepted, however, it is not clear why overseeding should occur with these high wind speed events unless the natural snow crystals are already critically small possibly due to small residence times within the cloud system.

a. Cloud physics model

The cloud physics model presented appears to be consistent with the observed climatology of natural snowfall at Wolf Creek Pass and Climax, Colorado. The daily snowfall at these locations reaches a maximum in the cloud top temperature range where effective natural ice nuclei and supply rates of cloud water combine in an optimum mode. The modification potential delineated by the model extends into colder cloud top temperatures for the higher upward speeds present in the Wolf Creek Pass area, and snowfall increases were observed when seeding events within this intermediate temperature range.

The modification potential delineated by the cloud physics model is generally verified by the results of the Climax and Wolf Creek Pass experiments. No increases of snowfall were observed when seeding events which the model indicated had sufficient natural ice nuclei. Large snowfall increases were observed in the cloud top temperature range where the model indicated a deficiency of effective natural ice nuclei. The agreement of the three independent samples with the model derived from current cloud physics knowledge validates the approach.

It is envisioned that a similar model could be used on a real time basis to control operational cloud seeding projects. The main obstacle to such an approach would be the development of numerical models that would yield acceptable vertical motion fields for the specific mountain barrier to be treated. Instrumentation will be needed which measures ice nuclei concentrations upwind and ice nuclei and ice crystal concentrations in the cloud system. This instrumentation should be amenable to rapid computer input. Serial rawindsondes, together with mountain top meteorological stations could supply the required meteorological input to the model. The desired treatment for the cloud system could then be computed and instigated. The model might include not only the maximizing of the precipitation process but optimizing the distribution of the snowfall on the mountain barrier.

The choice of mountain areas to be included in operational cloud seeding programs will probably depend significantly on their inherent modification potential. In order to intelligently define the modification potential for a specific area the following data is needed:

Distributions of natural precipitation with cloud height and cloud top temperature

Determine the relative importance of the diffusion and accretion processes

Determine effective ice nuclei concentrations in the area as a function of temperature

Determine the ratio of ice crystal concentration to ice nuclei concentrations in the area as a function of cloud top temperature.

Define the orographic component of the vertical motion field.

Present technology is now available to derive reasonable estimates of these quantities.

b. General conclusions

The agreement of the three independent samples with current cloud physics theory, and the internal consistency among the samples increase confidence that snowfall can be increased on the mountain barrier when seeding is conducted under the right conditions. Almost as apparent is the fact that snowfall can be decreased on the mountain summit when seeding improper conditions. The modest snowfall increases reported by most cloud seeding projects (generally 15% or less) appears to be composed of both increases and decreases that nearly cancel one another over a period of time. Clearly, a potential for modification does not always exist and cloud treatment will have to be tailored for existing conditions.

C. Weather Modification Geography

The Colorado River Basin above Lee's Ferry contains about 109,500 square miles. The average annual runoff for this Basin is equivalent to 2.3 inches of precipitation (Crow, 1967). Some 13% (about 14,200 square miles) of the area basin produces a runoff equivalent to 10 or more inches of precipitation. Some 9500 square miles produces from 1 to 10 inches, and the remainder of the Basin, some 85,800 square miles, produces runoff equivalent to about 1 inch or less of precipitation. This very large difference in yield of various portions of the Basin results from

1. The substantially greater amounts of precipitation in the mountainous areas resulting from orographic influences.
2. The greatly increased evapotranspiration losses at the lower elevations due to higher temperatures.

Clearly, the initial stages of a weather modification operational adaptation program in the Colorado River Basin should be concentrated in the 13% of the Basin that produces over 10 inches of precipitation and about 77% of the annual runoff.

1. Site Selection for Pilot Project

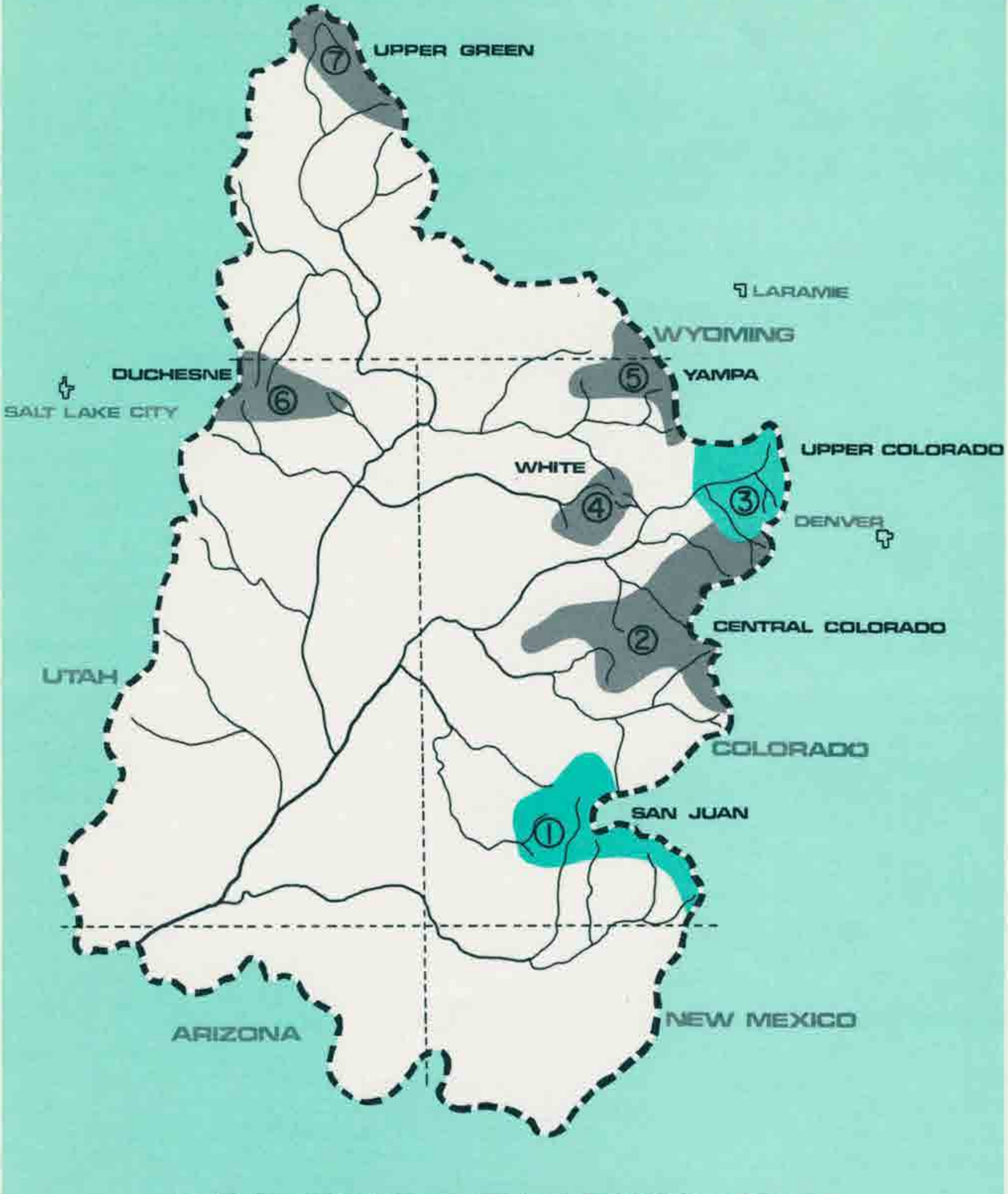
The 13% of the Colorado River Basin that produces most of the runoff lies almost exclusively above 9,000 feet elevation. The 9,000 to 10,000 ft contours, consequently, can be used to define the sub-areas of the basin that should receive primary consideration for initial weather modification efforts of a pilot project. Commercial programs of weather modification operations in mountainous areas have in general been conducted for individual watersheds. Moderate or large scale weather modification operations for larger sub-areas within the Colorado River drainage, however, will affect a number of such watersheds. Consequently, subdivisions of the Colorado River Basin for purposes of larger scale weather modification efforts should be defined for mountain massifs that should be the primary targets rather than individual drainage areas. Respective mountain massifs form the headwaters for a number of individual watersheds. The Colorado River Basin has, consequently, been divided into seven areas, (Figure 8) that form the primary targets for weather modification efforts to increase streamflow in the Basin. The seven sub-areas are:

1. San Juan Mountains
2. The central massif between the mainstem of the Colorado and the Gunnison Rivers
3. The Upper Basin of the Colorado River Basin above Kremmling
4. The White Mountains at the headwaters of the White River
5. The Park Range and headwaters of the Yampa River
6. The Uinta Mountains
7. The Wind River Range at the headwaters of the Green River

The critical areas of snow collection on several of the mountain massifs in these sub-areas can be noted from Figures 9 - 13. These aerial photographs of the respective mountain massifs were taken May 22-28, 1968. Figures 9 and 10 show the San Juan massif in the distance. Figure 9 shows the western portion of this range while Figure 10 shows the central portion. Figure 11 is a closer picture of the central portion of this range. By the May 22 date when the photograph was taken the lower elevation snowfall had melted and the remaining snowfall essentially defines the area above 9,000 to 10,000 ft msl that produces most streamflow. This can be seen from Figure 12 which shows the streamflow measured on Vallecito Creek which is fed primarily by snowmelt during late May, June, and early July in most years. This figure shows daily streamflow of 200 cfs or more had been recorded on only three days prior to the taking of the above aerial photographs of the area on May 22.

Following May 22, an additional 54 days had streamflow greater than 200 cfs, with the peak day reaching 1190 cfs on June 2. The snowmelt period in 1968 had a very noticeable dip in the middle of the season due to a cold spell with minimum temperatures being 25°, 27°, and 28°, respectively, on the three days when the streamflow dropped below 500 cfs.

Figure 13 shows the snowcover on the central Colorado River Massif, sub-area #2, from directly overhead. This photograph was also taken on 22 May 1968. Figure 14 shows the delineation of snowfall areas over another sub-basin area, sub-area #5, the Park Range. This photograph was made on May 28, 1968. Figures 15 - 20 show a closer view of the wintertime snowfall over these barriers and the base sites of three of the facilities for experimental program of weather modification. Figure 15 shows the CSU mountain laboratory (12,000 ft msl) atop Chalk Mountain in the central portion of the Colorado Rockies near Climax, sub-area #2. This is a fall season photograph. Figure 16 shows the same laboratory under a wintertime regime. Figures 17 and 18, respectively,



UPPER COLORADO RIVER DRAINAGE BASIN

Figure 8.

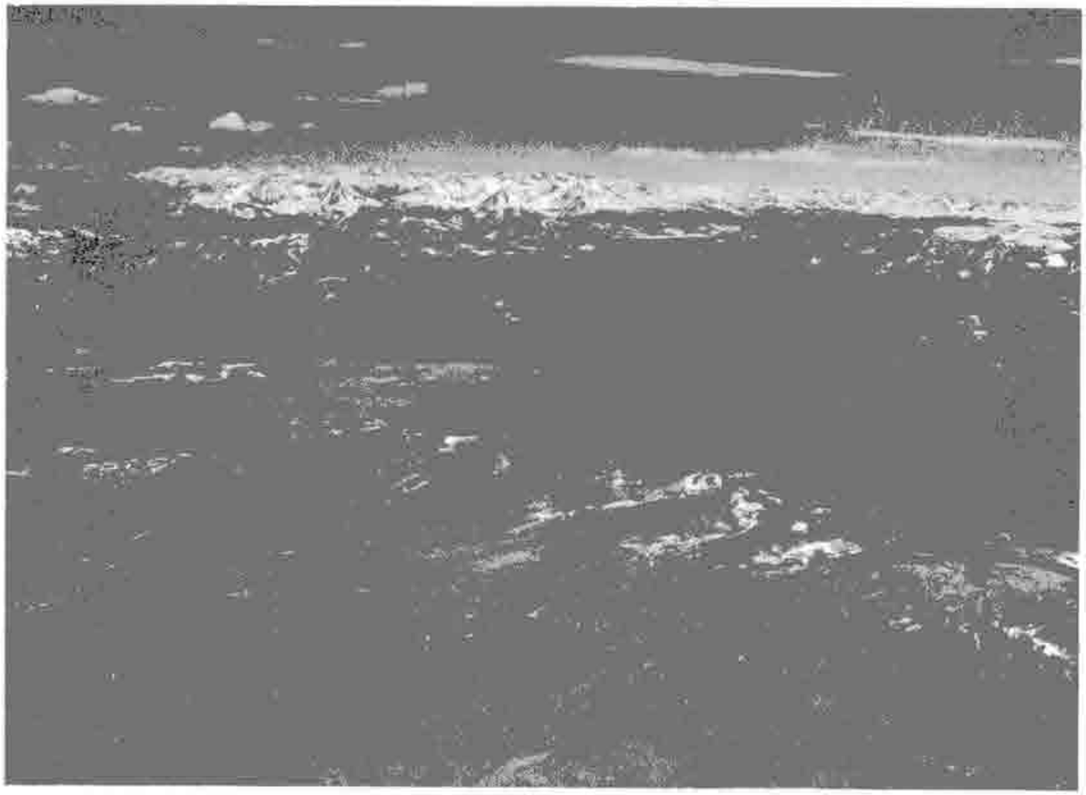


Figure 9.--Dolores River drainage looking N. E. towards Mount Wilson from 13,000 ft.

Figure 10.--San Juan River drainage. Highway goes to Pagosa Springs to the right. Looking north from 13,500 ft. Piedra River Drainage.

Figure 11.--From over Placerville looking east; San Miguel River Drainage from 13,500 ft., also showing Telluride, Colorado (circled).

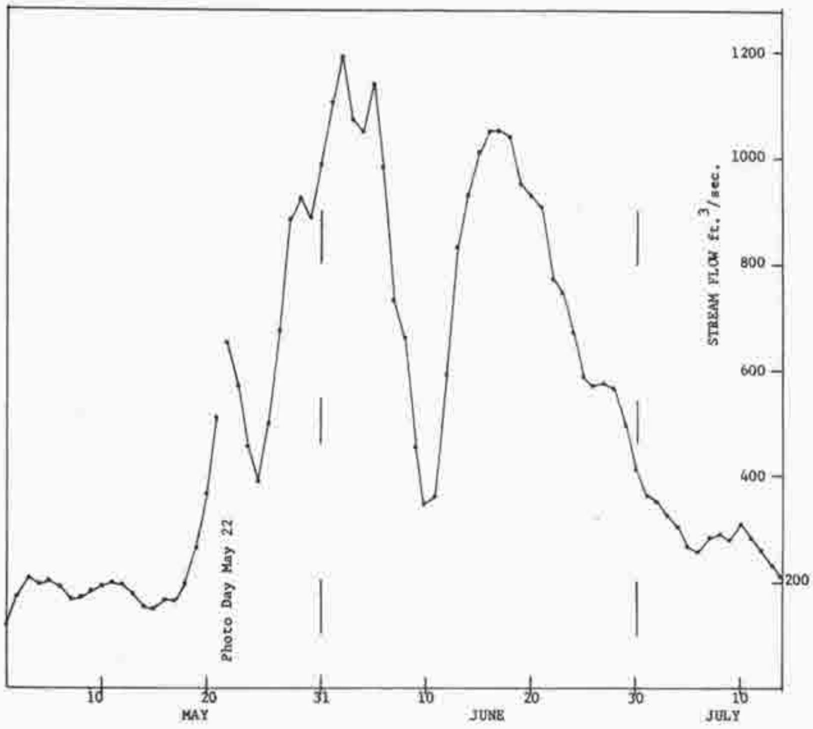


Figure 12.--Streamflow during 1968 snow-melt season measured on Vallecito Creek, station 9-3529, elevation 7906 feet msl., indicating nearly all of snow-melt runoff took place after aerial photographs made May 22, 1968.

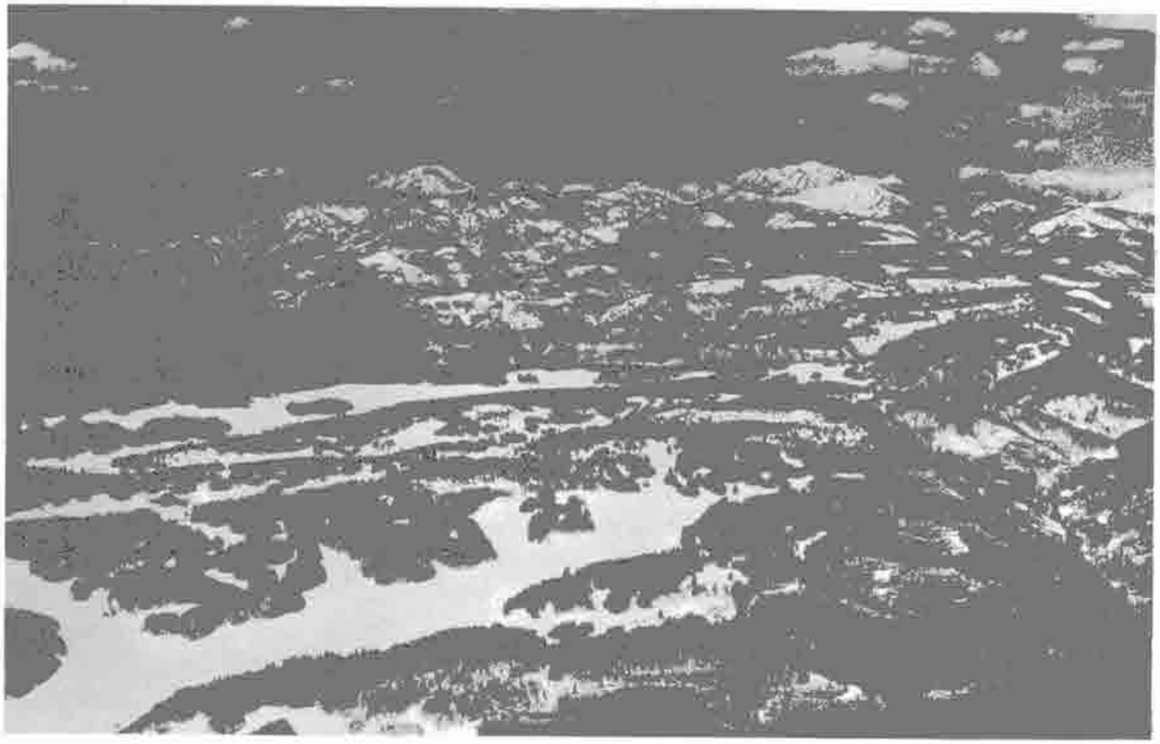


Figure 13. --Gunnison River drainage, Black Mesa in foreground, looking north from 13,000 ft.

Figure 14. --Yampa River drainage, Fish Creek.

Figure 15. --Colorado State University mountain laboratory atop Chalk Mountain near Climax, Colorado, 12,000 ft msl (close-up during fall season).

Figure 16. --CSU mountain laboratory atop Chalk Mountain near Climax, 12,000 ft msl (winter season).

Figure 17. --Access road to CSU mountain laboratory near Climax (winter).

Figure 18. --Access road to CSU mountain laboratory near Climax (summer).

Figure 19.--Schaefer Hut atop Elk Mountain in Southern Wyoming, 11,162 ft msl. Photo courtesy of Bureau of Reclamation.

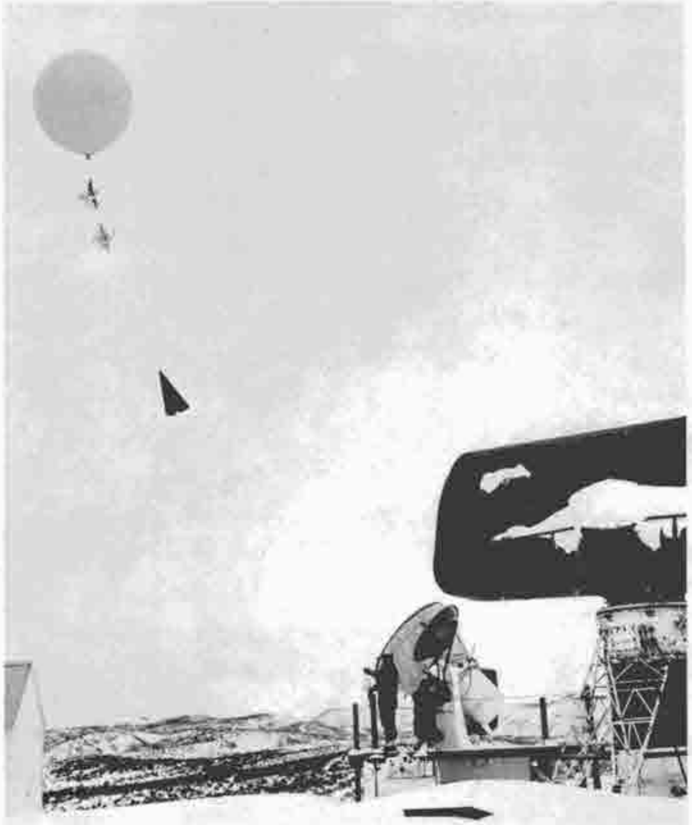
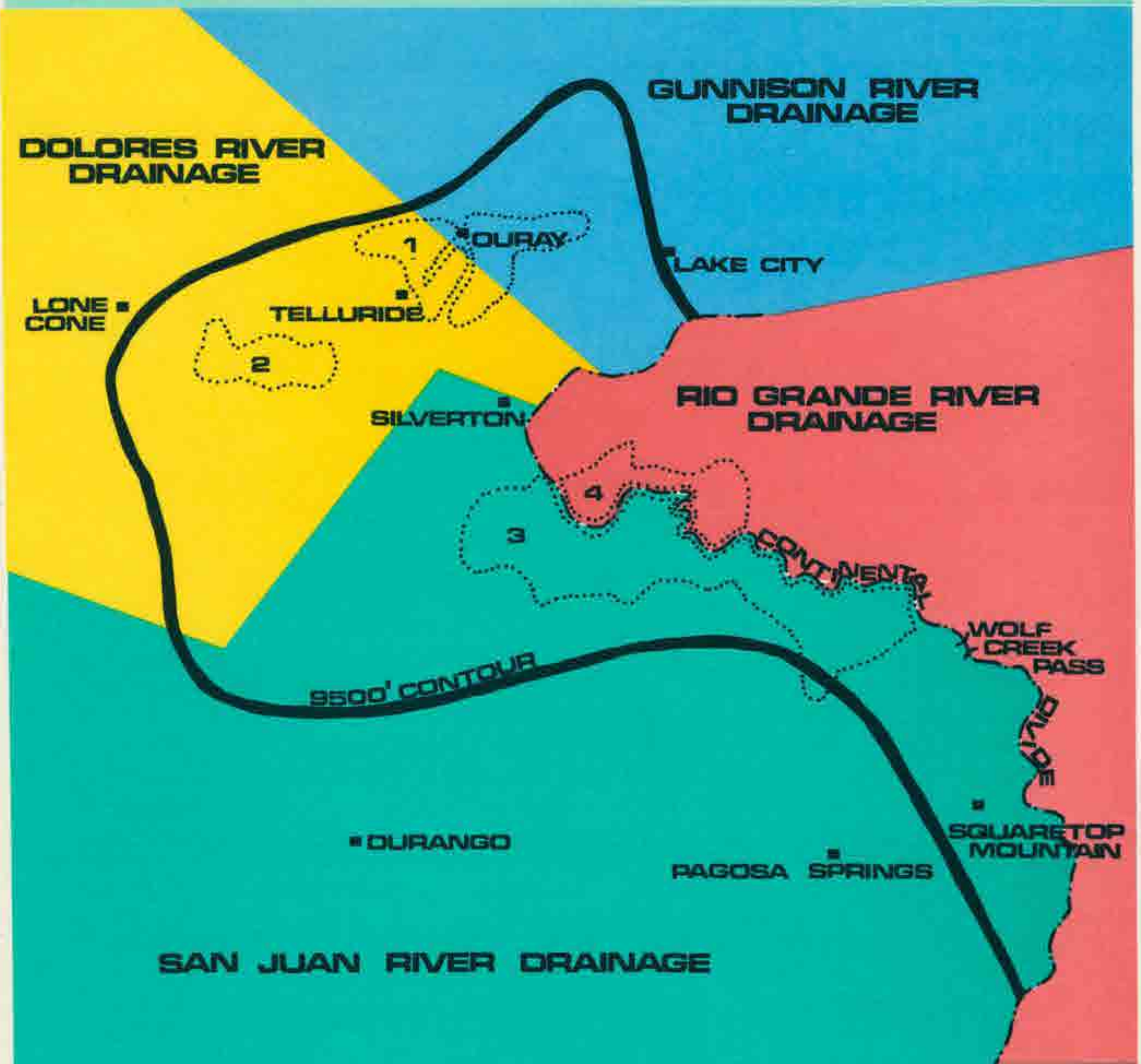


Figure 20.--Radiosonde release from Nike-Ajak radar station on top of Mount Harris. Photo courtesy of Bureau of Reclamation.

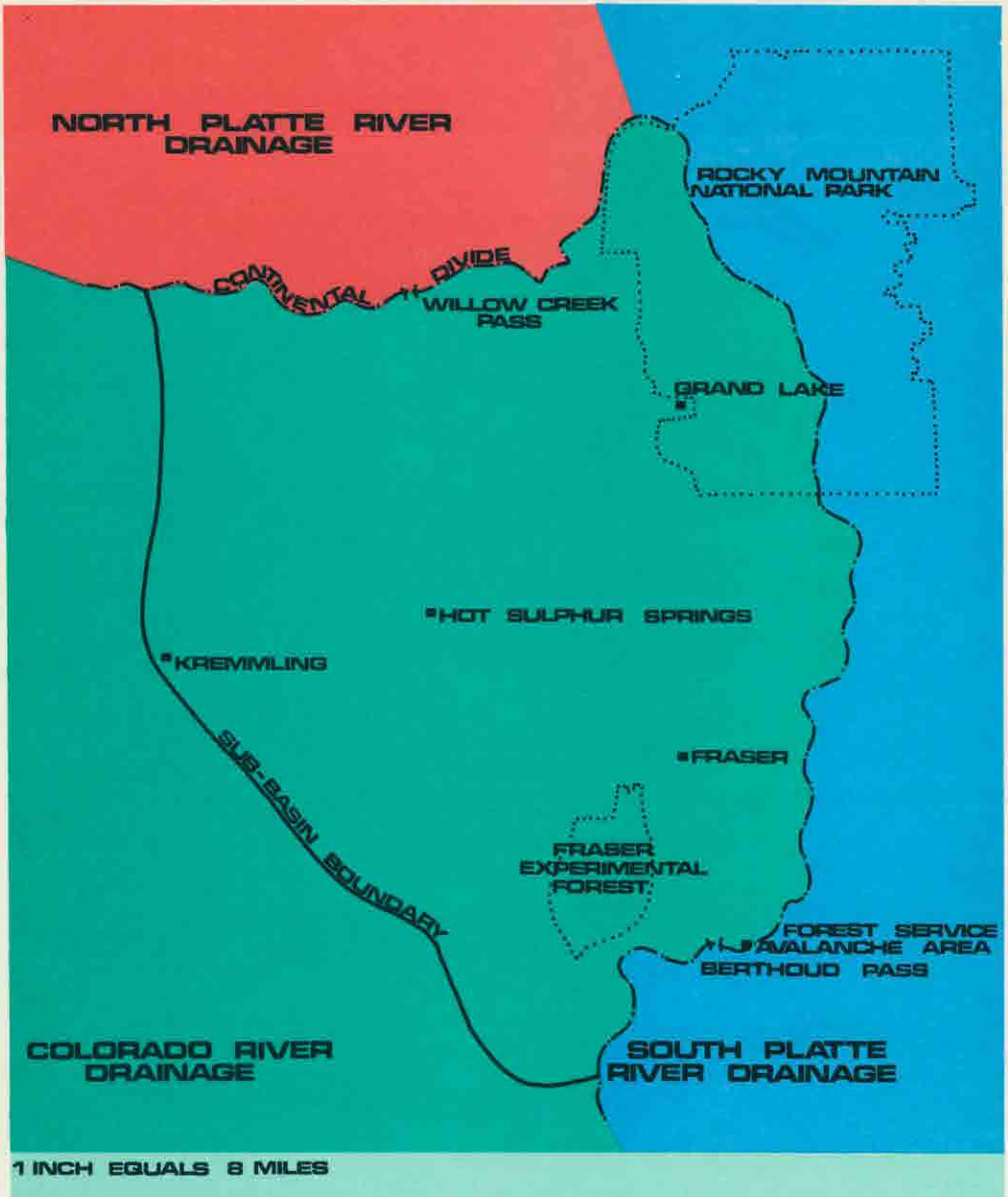


1 UNCOMPAHGRE WILD AREA
2 WILSON MOUNTAIN WILD AREA
3 SAN JUAN PRIMITIVE AREA
4 UPPER RIO GRANDE PRIMITIVE AREA

1 INCH EQUALS 15 MILES

SAN JUAN SUB-BASIN

Figure 21.



UPPER COLORADO SUB-BASIN

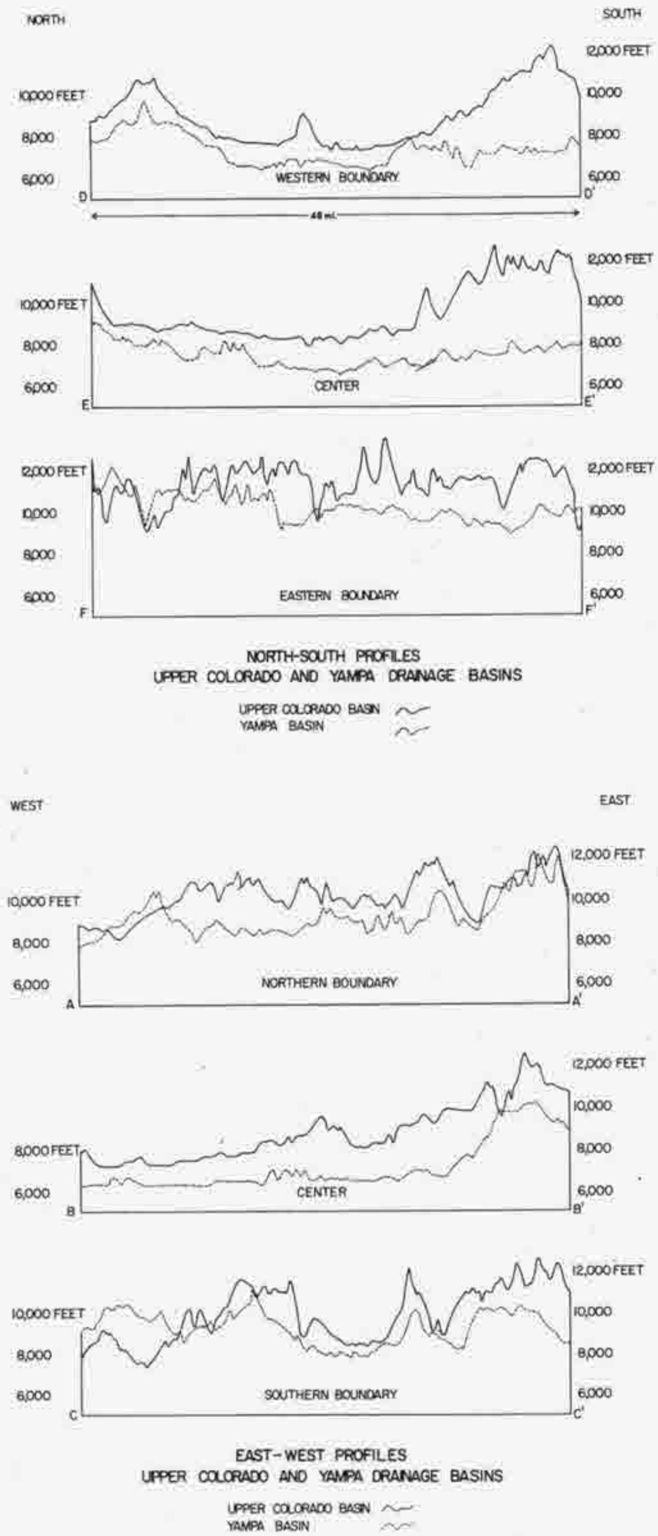
Figure 22.

show the access route to the laboratory under winter and summer conditions.

Figure 19 shows the crest of Elk Mountain (11,162 ft msl) in southern Wyoming during early February 1966. This is an important base for the field experimentation being carried out by the University of Wyoming. Additional experimental studies have been carried out in the Park Range of northwestern Colorado, sub-area #5, by Bollay, Associates. Figure 20 shows their radar-radiosonde station on top of Mount Harris.

Two of the sub-areas have been given primary attention as a location for an initial pilot project. They are: (1) The San Juan Mountains and (2) The Upper Basin of the Colorado River. The San Juan area includes drainage areas from Lake Fork to the New Mexico border and is shown in Figure 21. The Upper Basin includes drainage areas from Williams Fork to Troublesome Creek and is shown in Figure 22. The recommendations of these two areas is based upon the following considerations:

1. Both basins make a substantial contribution to the flow of the water in the Colorado River Basin. This is true in terms of either water supplied per unit area or of total flow.
2. It is highly desirable that sub-areas of the Colorado River Basin located near the eastern extremity of the Basin serve as initial pilot projects. This will allow experimental-type cloud physics and weather modification programs to be carried out in upwind areas of the Colorado River Basin without the hinderance of upwind seeding. This becomes extremely important when one considers that within 10 to 15 years, weather modification operations will probably be routinely carried out for large portions of this and other basins. Consequently, the opportunity to explore and learn in a natural environment may cease to exist. Development of operational-type programs, east to west across the Basin, would maximize the interval of time available for continued development of seeding technology under uncontaminated conditions.
3. Substantial operational facilities, in addition to regular ESSA, USGS, SCS, etc., facilities are available in support of the design efforts and future operational programs in these areas. Streamflow and precipitation data for the Upper Basin area are available for many years from the Forest and Range Experiment Station. The data include high elevation precipitation and weather data collected at the Fraser Experimental Station and at the Avalanche Research Station at Berthoud Pass. Additional precipitation profile data for Berthoud Pass have been collected by Colorado State University. In the case of the San Juan, four years of precipitation data for Wolf Creek Pass are available through the Atmospheric Science group at Colorado State University.
4. The use of these two specific orographic barriers will provide a test of cloud seeding operations under widely differing topographic conditions. A large section of the San Juan Range, for example, can frequently be nearly parallel to the airflow from important storms. The Upper Basin, in contrast, is primarily perpendicular to airflow in major storms. Weather modification models being developed at Colorado State University indicate that the method of operations and the results to be expected from weather modification operations should be highly variable as a function of topographic profile and orientation.
5. As weather modification becomes a major endeavor, water right conflicts in the immediate vicinity and in more distant locations could develop. These two areas could serve very adequately to test a wide variety of such problems.
6. Pilot programs in these two areas could also have important beneficial effects on watersheds outside the Colorado River Basin. Seeding operations could affect the Rio Grande Basin, an area consistently in need of increased water supplies, when seeding is carried out for the San Juans. The South Platte and North Platte basins could also be affected from seeding for the Upper Basin. The transdiversion of water into the Big Thompson system from the Upper Basin could have additional value. These possibilities of beneficial effects downwind of the Colorado River Basin could adequately be tested by the use of these two specific areas.
7. In the case of the Upper Basin of the Colorado River, the complications introduced from access restrictions to the wilderness areas is minimized in comparison to those of other areas.
8. The two areas proposed are large enough to properly permit determination of atmospheric water balances. These determinations hold promise of providing a very important method of monitoring basin water supply.
9. The Park Range, for which extensive meteorological observations have been made during the past four years, could serve as an excellent control area for an Upper Basin seeding target. It is upwind of the Upper Basin and the terrain of the two basins is quite similar (Figure 23).
10. Considerations of the physical model describing the potential for weather modification and the results from the Climax and Wolf Creek experiments indicate that the San Juan area should have the greatest potential for water augmentation. This results from the warmer average cloud temperatures and a rapid lifting of the air mass over the San Juan Range which produces strong vertical motions.



NORTH
SOUTH
12,000 FEET
10,000 FEET
10,000
8,000
6,000
WESTERN BOUNDARY
D
D'
10,000 FEET
12,000 FEET
CENTER
E
E'
12,000 FEET
EASTERN BOUNDARY
F
F'
NORTH-SOUTH PROFILES
UPPER COLORADO AND YAMPA DRAINAGE BASINS
UPPER COLORADO BASIN
YAMPA BASIN
WEST
EAST
12,000 FEET
10,000 FEET
NORTHERN BOUNDARY
A
A'
8,000 FEET
CENTER
B
B'
SOUTHERN BOUNDARY
C
C'
EAST-WEST PROFILES
UPPER COLORADO AND YAMPA DRAINAGE BASINS
UPPER COLORADO BASIN
YAMPA BASIN

Figure 23

The San Juan Mountains are being given primary consideration for the initial pilot project.

2. Maps

A base map, scale 1:125,000 has been constructed for each of the sub-basins. (Shobe, 1969). These base maps contain a variety of information including:

1. Topographic contours
2. Roads
3. Streamgages
4. Snow courses
5. Ski areas
6. Climatological station
7. Power lines
8. Fire look-out stations
9. Communication facilities
10. Etc.

It is anticipated that repeated reference will be made to this map, during both the design and operational phases of the pilot projects in the basin.

The following is a summary of the procedure used in the construction of these base maps:

a. A series of topographic maps scaled 1:250,000 were spliced and trimmed to include the major areas of interest in each of the sub-basins and extended some 30 miles beyond. These topographic maps were produced by the Army Maps Services and are published and distributed by the U.S. Geological Survey.

   The contour interval of 200 ft is believed to give sufficient detail for this program. Also, the 30-mile extension is considered sufficient for locating most instrumentation relevant to program planning for the specific sub-areas.

b. The topographic maps were photographically enlarged to a scale of 1:125,000 (approximately $\frac{1}{2}$ inch = 1 mile). This scale is considered sufficient to give the desired detail in connection with the location of roads, streamgaging sites, topography, etc., without being excessively bulky.

c. Supplemental data of specific interest to the project has been collected and plotted on these base maps. The supplemental information placed on these maps has been color-coded to aid in the location and identification of the specific types of information.

   The following is a list of the information plotted on the base maps and the source of the respective data:

   (1) Sub-basin outline
   The outline of the sub-basins has been determined primarily by the elevation of the land areas. Elevations above 10,000 ft in the southern part of the upper part of the Colorado River Basin and 9,000 ft in the northern portion have been used. These areas are delineated by a heavy line on these maps.

   (2) Restricted areas
   Restricted areas, primitive areas, national parks, wilderness areas, and natural areas, have been outlined in red. Most of these areas prohibit any type of motor vehicle or instrumentation within their borders. Twelve of these areas, for example, are within the sub-basin outline for the San Juan Mountains with an additional nine within the 30-mile boundary area.

   (3) Topographic contours
   The topographic contours at 200 ft intervals are those enlarged from the original maps.

   (4) Roads
   Major roads are part of the original maps. A large number of secondary roads and jeep trails have been added. These roads are of importance for planning the installation and servicing of observational and seeding equipment. The primary source of additional road information has been the U.S. Forest Service maps of the 19 national forests in and surrounding the drainage basin.
   Where it is feasible, the roads are color-coded as to accessibility; i.e., winter accessibility, or summer accessibility only. The source of this information has been the U.S. Forest Service stations, highway department in the local areas, sheriffs' offices, etc.

   (5) Streamgaging stations
   Streamgaging stations have been plotted according to the following information:

   (a) Compilation of records of surface waters of the United States to Sept. 1950, Part IX Colorado River Basin, Water Supply Paper Number 1313, U.S.G.S.

   (b) Compilations of records of surface waters of the United States, October 1950 to September 1960, Part IX, Colorado River Basin, Water Supply Paper Number 1733, U.S.G.S.

   (6) Snow courses
   The data for the location of snow depth measurement has been obtained from the following sources:

   (a) Summary of Snow Survey Measurements, Colorado and New Mexico, 1936-1963. U.S. Department of Agriculture, Soil Conservation Service.

   (b) Summary of Snow Survey Measurements, Wyoming, 1919-1967. U.S. Department of Agriculture Soil Conservation Service.

   (7) Climatological stations
   The location and type of service of the various climatological stations was obtained from the following publications

   (a) Climatological Data, Colorado. U.S.

Department of Commerce, Environmental Science Services Administration, Weather Bureau

(b) Climatological Data, Wyoming. U.S. Department of Commerce, Environmental Science Services Administration, Weather Bureau

(8) Ski areas

Sources for the location of the ski areas have been:

(a) Colorado Skiing, publication of the Colorado Visitors Bureau, 225 West Colfax, Denver, Colorado

(b) Forest Service maps

(c) State highway maps

(9) Power lines

Major electrical power line transmissions have been added to the Basin map of the Upper Colorado River collection area and the San Juan collection basins. This information has been supplied by the local electric associations. In Colorado most of the associations serve a small area. Therefore, a number of offices have been contacted. The following associations have supplied information:

(a) Empire Electric Association, Inc., Cortez, Colorado

(b) LaPlata Electric Association, Inc., Durango, Colorado

(c) Mountain Parks Electric, Inc., Granby, Colorado

(d) The San Miguel Power Association, Inc., Nucla, Colorado

(e) The Western Colorado Power Company, Montrose, Colorado

Additional power transmission lines are being added to the base map for other subareas as information is received.

(10) Communication lines

Major telephone transmission lines are not yet added to the maps. Mountain States Telephone Company has indicated that they will supply maps of their lines that serve specific areas when they receive a list of specific sites where communications are desired. The location of their major lines over large areas are not readily available.

(11) Permanent look-out stations

The locations of permanent look-out stations have been transferred from Forest Service maps to the sub-basin map.

(12) Forested areas

Overlays of the forested portions of the major areas of interest are being constructed. The non-forest areas as may be used for instrumentation or possibly landing sites are being emphasized. U.S.G.S. Survey maps are the source of this information.

(13) Overlays of proposed instrumentation

Overlays of proposed sites for precipitation gages, streamgages, and seeding generators have been prepared for the Upper Colorado River and the San Juan collection basins. The major portion of this map work has been completed. Up-dating and revision of the information will continue as necessary.

D. Weather Modification Climatology

The material presented in this section describes certain natural climatic characteristics of the Basin. The specific items included serve as background in formulating the program design. They include a description of certain characteristics of the precipitation, snowfall accumulations, temperature regimes, and of the upper air conditions controlling the formation of both natural and artificial precipitation. Much of the material is presented for the Climax area due to the ready availability of background data. This material should apply, at least in a general way, to most of the important subareas of the Basin in central and northern Colorado. Climatic conditions in the San Juan Mountains are substantially different in many aspects and are, consequently, presented separately.

1. Surface Climatology

a. Hourly precipitation

(1) Hourly precipitation rates

The substantial accumulation of snowcover over the Colorado Rockies during the winter season results from many hours of snow falling at a very low rate. Figure 24 shows the distribution of hourly precipitation intensities (a) and of total snowfall (b) at Climax for the period November through May 1964-67. Snowfall occurs at a water equivalent rate of .02 inch per hour or less 71% of the time and at .04 inch per hour or less 89% of the time. Rates in excess of .20 inch per hour do not occur. The high frequency of snowfall at the lower intensities is so marked that these lower intensities also account for most of the snowfall. 42% of the total snowfall occurs at the rate of .02 inch per hour or less, 68% at the rate of .04 inch or less, and 91% of the total snowfall occurs at the rate of .08 inch per hour or less.

It can be seen from Figure 25 that there are also many hours of low intensity snowfall in the San Juan area of the southern part of the Colorado River Basin. Six hourly reporting stations are available for this general area, although only two are above 9,000 ft msl and none are located in the highest precipitation areas. The

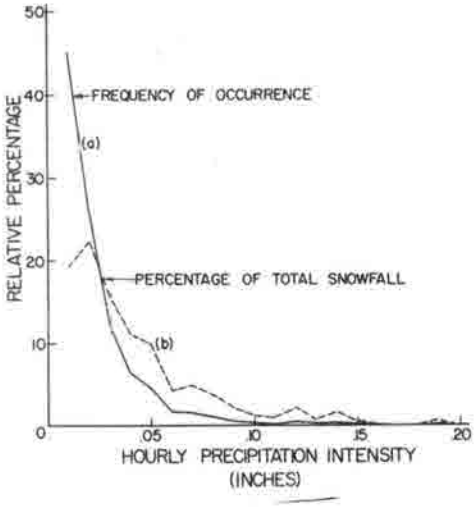


Figure 24. --Distribution of snowfall at Climax, Colorado, as a function of the hourly intensity. Data is for November through May, 1964-67.

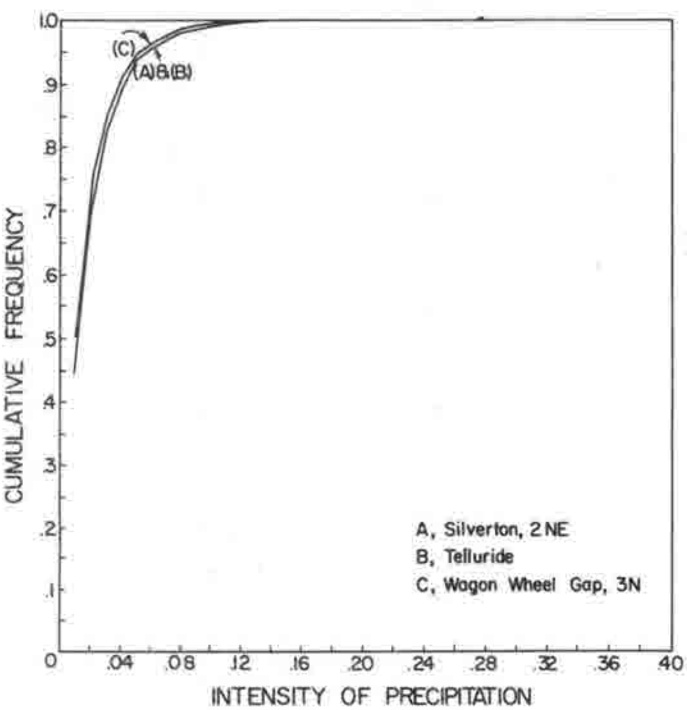


Figure 25. --Cumulative distribution of snowfall intensity at San Juan Mountain stations, November through April, 1948-1968.

sample period in this case is the 20-year period, November 1948 to April 1968. Silverton (Curve A, Figure 25) shows that the hourly precipitation rates are .02 inch per hour or less 70% of the time, and .04 inch per hour or less 89% of the time. The cumulative curves of precipitation frequency for Telluride (Curve B, Figure 25), another San Juan Mountain precipitation station, and for Wagonwheel Gap (Curve C, Figure 25), a station to the lee of the San Juan Mountains are quite similar.

Lower elevation and upwind stations in the San Juan area exhibit a somewhat greater proportion of higher precipitation intensities but actual values are still low. This somewhat greater proportion of higher hourly intensities is believed to result from reduced amounts of precipitation received from orographic influences compared with that received from storm situations having deeper cloud systems. Even for these stations, as can be seen for Durango (Curve A, Figure 26), some 60% of the hourly precipitation still occurs at intensities of .02 inch or less and .04 inch per hour or less is experienced 80% of the time.

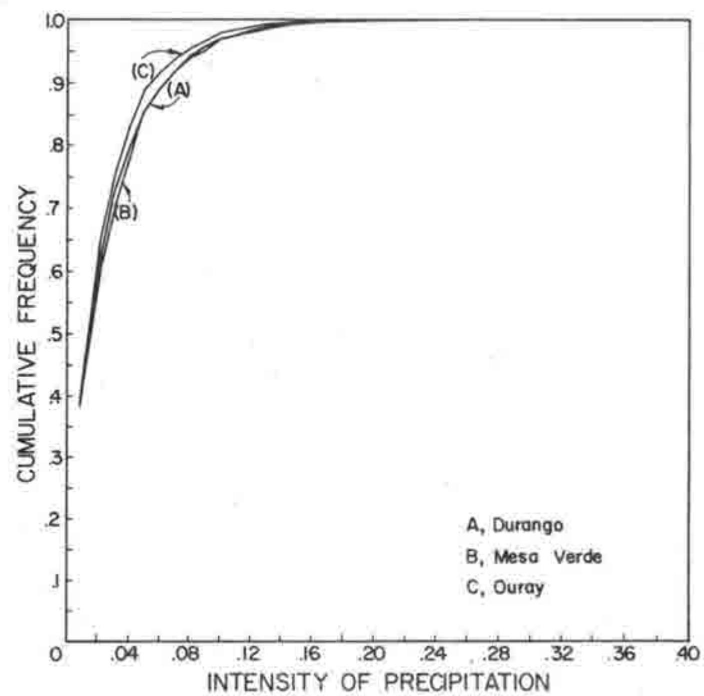


Figure 26. --Cumulative distribution of snowfall intensity at lower elevation stations in the San Juan area, November through April, 1948-1968.

The few hours of higher intensity precipitation in the San Juans make a greater contribution to the total snowfall than at Climax, however. Despite this, it can be seen that for Silverton (Curve A, Figure 27), for example, some 40% of the total snowfall still occurs at intensities of .02 inch per hour or less, 67% at .04 inch per hour or less, and some 90% at .08 inch per hour or less. The contribution of the higher snowfall intensities is more apparent at the upwind and lower elevation precipitation stations in the San Juans. Figure 28 shows, for example, at Durango (Curve A) that only 26% of the snowfall occurs at intensities of .02 inch per hour or less, less than half (46%) occurs at intensities .04 inch per hour or less, and that only 78% of the snowfall occurs at intensities of .08 inch per hour or less. This is believed to again reflect the greater percentage of precipitation at these stations resulting from general storm conditions in contrast to that from orographic influences. Durango and Mesa Verde are on the south and southwest side of the San Juan Mountains, while Ouray represents a lower elevation station on the north side of the range. It can be noted that the contribution of the higher snowfall rates at Ouray is less than at Durango or Mesa Verde, but still greater than at the higher mountain stations of Silverton and Telluride.

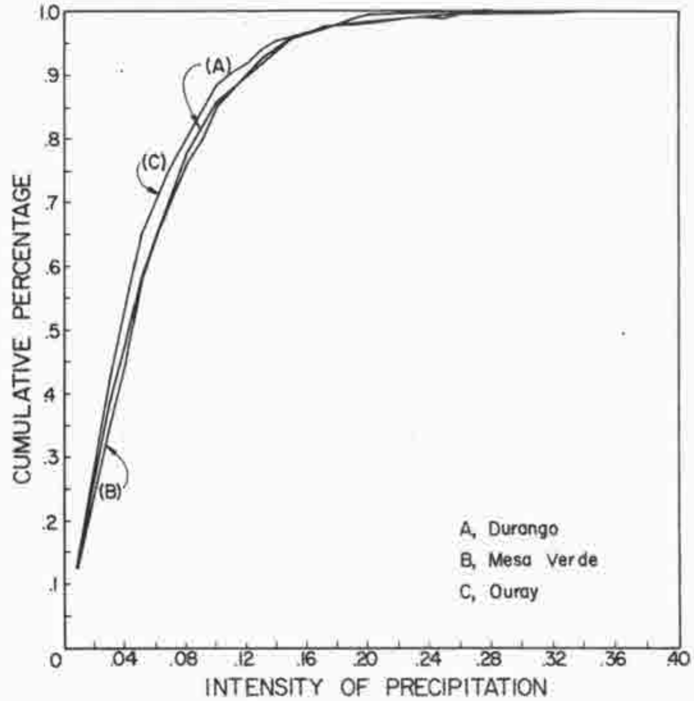


Figure 28. --Cumulative contribution of precipitation intensities to total snowfall, November through April 1948-1968.

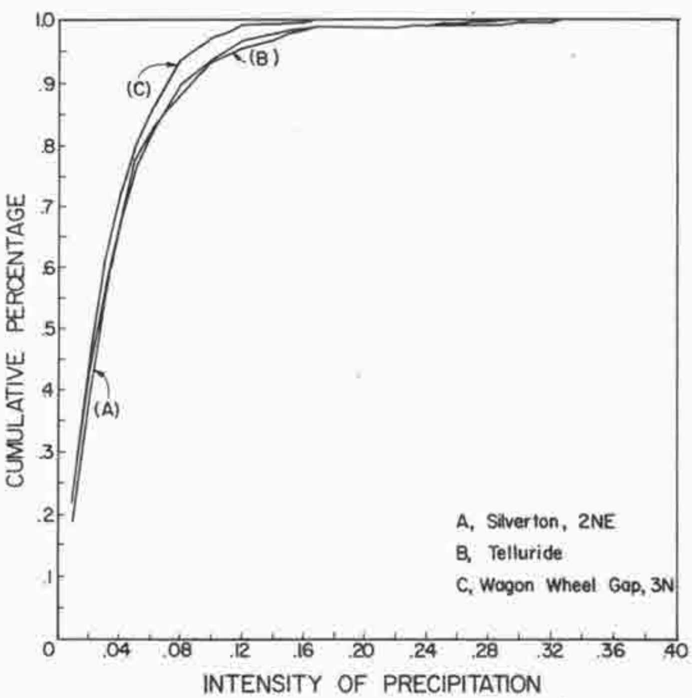


Figure 27. --Cumulative contribution of precipitation intensities to total snowfall, November through April 1948-68.

In summary of this sub-section, it is clear that many hours of precipitation falling at low rates accumulate to form the snowpack in the Colorado mountain areas. Hourly intensities in the San Juan Mountains are somewhat higher than those experienced in the northern portions of the Colorado River Basin; and the hourly intensities at the lower elevations, particularly those south of the San Juans, are highest. These stations are not reflecting the many hours of precipitation resulting from purely orographic influences.

(2) Diurnal variation of hourly precipitation

Knowledge of the diurnal variation of precipitation is essential for formulating appropriate program design and program operations. This is particularly apparent in the north portion of the Colorado River Basin where the diurnal variation of precipitation is very substantial. Distribution of snowfall with respect to the time of day and according to hourly intensities are shown in Figure 29 for three winter seasons (1964-67) at Climax, Colorado. It can be seen from Curve A that a

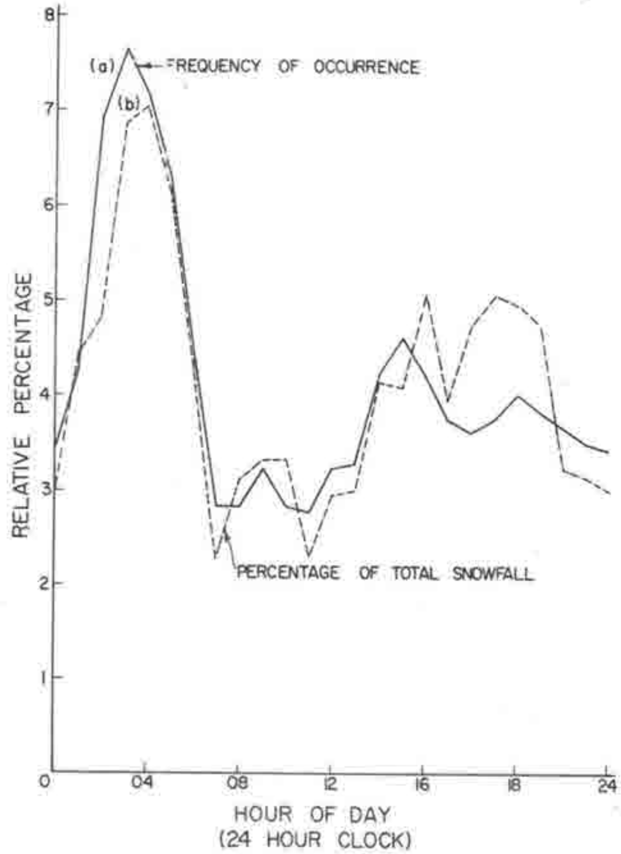


Figure 29. --Distribution of snowfall at Climax, Colorado, as a function of the hour of day, November through May, 1964-67.

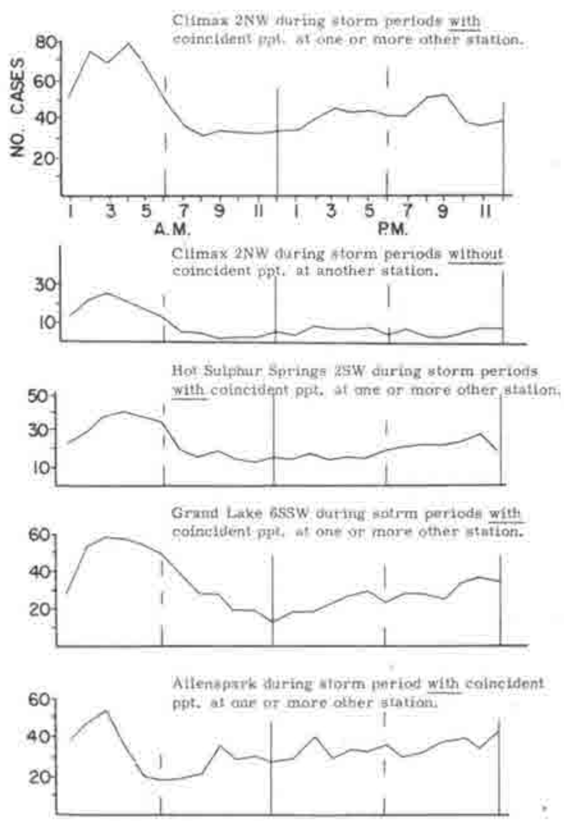


Figure 30. --Six month diurnal frequency pattern of hourly precipitation, November - April for three seasons, at four stations in or near the Upper Colorado River area above Kremmling.

marked peak in the occurrence of snow occurs at around 0300 Mountain Standard Time. A pronounced minimum in occurrence exists from 0700 to 1100 MST, followed by smaller secondary peaks during the afternoon and evening. The probability of precipitation at 0300 MST at Climax is almost three times that for the period from 0700 to 1100 MST. It can also be seen from Figure 29 (Curve B) that the percentage of total snowfall follows very much the same diurnal variation. Hourly intensities are slightly lower between 0200 and 0400 MST and somewhat higher between 1600 and 2100.

Consideration of hourly snowfall for Climax, Colorado, yields many interesting facts that are typical of many reporting stations in the Colorado Rockies. The marked peak in frequency during the early morning hours followed by the dip in the forenoon hours is typical of most central and northern Colorado stations. This can be seen from Figure 30 which shows the number of cases of coincident precipitation at Climax, Hot Sulphur Springs, Grand Lake 6SSW, and Allenspark.

The broad minimum in precipitation activity between 0700 and 1100 MST provides an excellent starting time for an experimental day since this represents the bottom in a pronounced diurnal cycle. New meteorological data required for decision-making arrives during this same time interval and the combination of the two factors suggests that this interval provides an excellent opportunity for the start of a 24-hour experimental unit. It also provides for observation periods relatively free from the complications of falling snow contributing to the collection of better data. It is essential that the experimental unit used for research programs in the northern Colorado Rockies take this diurnal variation into account, since the 300% variation in precipitation over a day can far exceed results expected from modification efforts. A very slight imbalance in the sample size as a function of the time of day for an experimental unit of only a few hours could substantially override seeding results.

The large diurnal maxima in the frequency of precipitation during the early morning hours at Climax is also apparent (Figure 31) for the precipitation stations at Ouray and Wagonwheel Gap in the San Juan

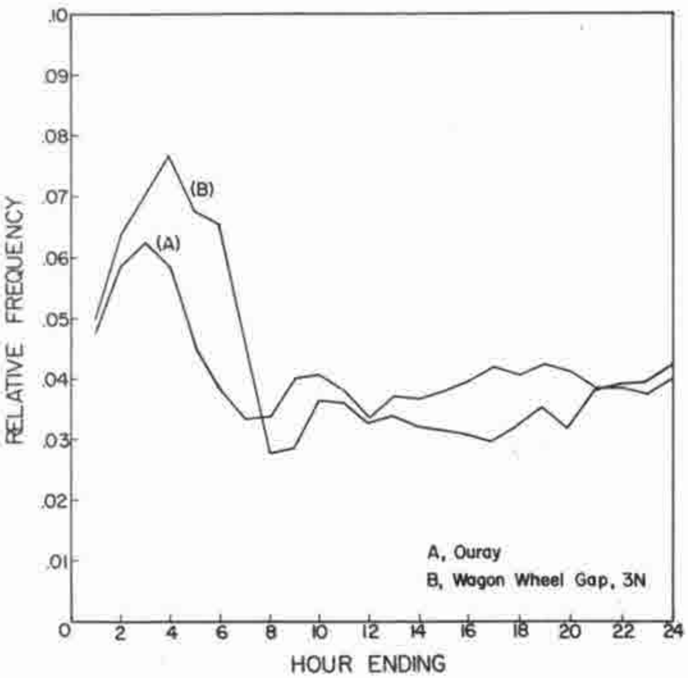


Figure 31.--Diurnal frequency of snowfall at Ouray and Wagonwheel Gap, November - April, 1948-1968.

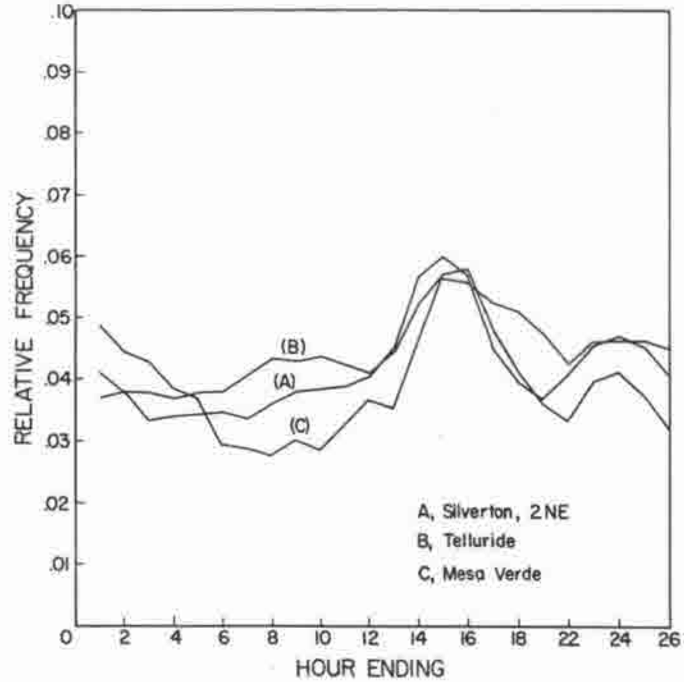


Figure 33.--Diurnal frequency of snowfall at Silverton, 2NE, Telluride, and Mesa Verde, November - April, 1948-1968.

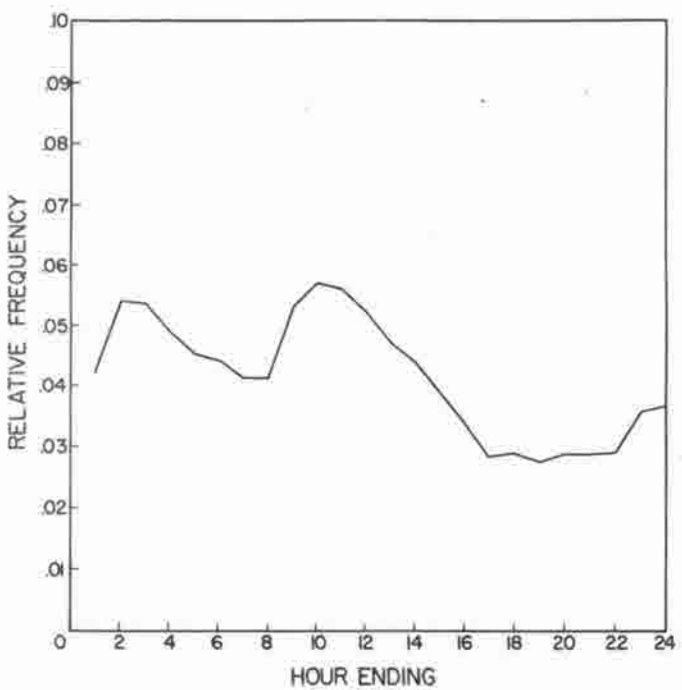


Figure 32.--Diurnal frequency of snowfall at Durango, November - April, 1948-1968.

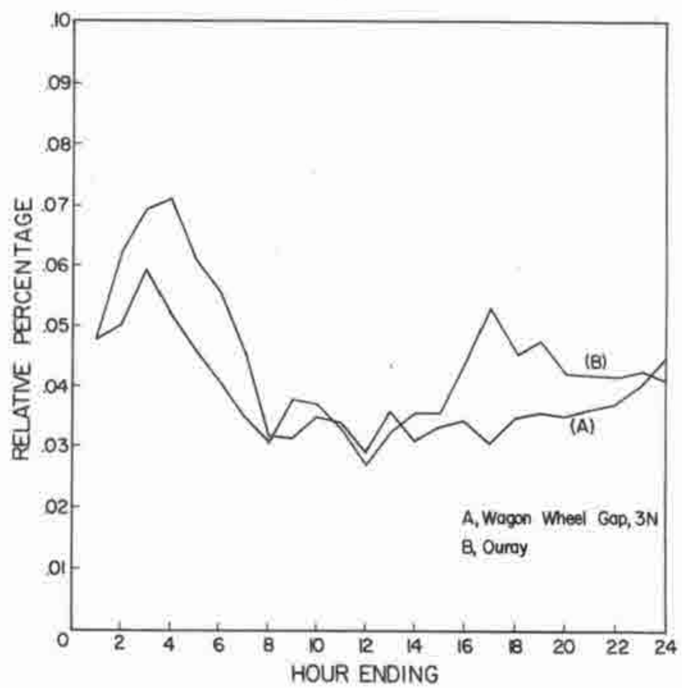


Figure 34.--Relative per cent of daily snowfall occurring at the respective hours of the day, November - April, 1948-1968.

area. These are both stations that are frequently downwind of the mountain barrier during substantial snowfall episodes. At an upwind station at Durango (Figure 32), the pattern is considerably altered with a diurnal maximum precipitation occurring during mid-morning and a diurnal minimum during the late afternoon or early evening. Despite this change in pattern it can still be noted from Figure 32, that the diurnal maximum is about twice that occurring during the minimum. The diurnal pattern of precipitation is shifted to even later in the day for the mountain stations in the San Juan area where a late afternoon maximum can be observed. Figure 33 shows this effect for Silverton, Telluride, and Mesa Verde. The maxima are also clear for these stations and represents a value some one-and-one-half to twice as great as that experienced at hours of lowest precipitation frequency.

Figure 34 shows that the relative percent of daily snowfall occurring at the respective hours of the day follows the same general diurnal trend observed for the frequency of snowfall. There is a broad crest of larger total amounts between 0100 and 0600 at Wagonwheel Gap 3N. At Ouray two peaks can be identified with noon being the lowest hour of the day.

It is clear that the diurnal variation of precipitation should be considered in experimental design and in the conduct of operations in the San Juan area as well as in the other portions of the Colorado River Basin. The variation in the time of the diurnal peaks and troughs in relation to terrain needs to have special consideration in the case of the San Juan area. It is expected that studies in progress will increasingly define the precipitation processes in these basins through an improved understanding of the diurnal variation of precipitation.

(3) Number of hours of precipitation

The hourly precipiation gage at Berthoud Pass in the Upper Basin of the Colorado River recorded an average of 503 hours of precipitation, November - April, 1965-1968. This consisted on the average of 495 hours at .05 inch per hour or less, 7 hours at from .06 to .10 inch per hour and 1 hour at greater than .10 inch. Some 10% to 20% of the hours with precipitation was not measured, primarily due to clock stoppage. After an adjustment for this missing data is made, it is estimated that the Berthoud Pass area receives about 600 hours of precipitation of .01 inch per hour or greater. It could be expected that the hourly precipitation would be .05 inch per hour or less on 591 of these hours, .06 to .10 inch per hour on 8 hours and greater than .10 inch per hour on 1 hour. The number of hours when there is precipitation in the area is considerably greater than when there is precipitation at a single station. It is, therefore, estimated that there are greater than 700 to 800 hours of precipitation at intensities greater than .01 inch per hour in the Upper Basin of the Colorado River. More than 96% of these can be expected to be at an intensity of less than .05 inch per hour.

In the 20-year period November 1948 to April 1968, Telluride in the San Juan Mountains had an average of 248 hours per year when precipitation at intensities of .05 inch per hour or less was recorded, 13 hours when the intensity was .06 to .10 inch per hour and 3 hours when the intensity was greater than .10 inch per hour. This gives a total of 264 hours when distinct hourly precipitation amounts were recorded. Many hours of data were lost, however, due to various causes, clock stoppage and gage bridging being two of the most important. The average winter precipitation from cumulative daily readings at Telluride during the 1931-60 interval was 11.82 inches. The average precipitation given by the incomplete hourly record, however, was only 6.08 inches. If a proportionate adjustment is made to the number of hours of precipitation in accordance with the percent of total hourly precipitation recorded to the total daily precipitation measured it can be estimated that there is an average of 514 hours of precipitation each winter at Telluride. It could be expected that the precipitation would be .05 inch per hour or less for 484 hours, .05 to .10 inch during 25 hours, and greater than .10 inch on 5 hours. Some stations, Wolf Creek Pass for example, receive more than twice as much precipitation on the average during a winter season as Telluride (24.87 inches to 11.82 inches). Furthermore, the number of hours when there is precipitation at points in the entire San Juan area is considerably greater than when there is precipitation at any single station. It does not seem unreasonable, therefore, to estimate that there are at least 700 to 800 hours of precipitation in the San Juan Mountains during an average winter.

Investigations are in progress to refine the above estimates and extend them in order to determine the number of hours that can be expected for various meteorological conditions with varying degrees of suitability for weather modification operations.

b. Daily precipitation

The average wintertime precipitation (November - April) between November 1953 and April 1960 at Climax was 14.14 inches. Since the average number of days with precipitation during this interval was 85, the mean daily precipitation on days with precipitation was .17 inch. The average of 85 days with snowfall per winter season amounts to 47%, or almost half, of the 181 days during the November - April period. 35% of the days with precipitation had .06 inch or less, 50% had .11 inch of less, 80% had .26 inch or less, and the extreme value recorded was .95 inch. 90% of all the daily precipitation events during this interval were in the range from .03 to .50 inch. While Climax is representative of much of the area that accumulates snowpack in the northern Colorado Rockies, many higher elevations and areas exposed to stronger orographic influences receive total winter snowfall of nearly double the Climax amount. The additional snowfall at these locations results both from additional days of snowfall and from somewhat greater daily amounts. The general pattern of light snowfall with precipitation occurring on about half of all winter days is representative, however, of all important snow-producing areas of the northern and central Colorado Rockies. This can be seen from Table XI. This shows the monthly, seasonal, and 3-year average precipitation and the number of precipitation days for Berthoud Pass, Fraser, Grand Lake, and Hot Sulphur Springs. All of these stations are in the Upper Basin of the Colorado River. Berthoud Pass is in one of the higher precipitation areas. Most daily snowfalls, even in the heavier snow areas, are less than .20 inch per day with daily totals greater than 1 inch very infrequent.

The three season (1964-67) record of days with greater than .40 inch per day for Berthoud Pass is shown in Table XII. It can be noted that there were four days in three years with daily precipitation greater than 1 inch, the greatest being 1.27 inches. It can be noted further that there were only nine days in the three years (average of 3 per year) with daily precipitation as great as .75 inch per day.

In contrast to the northern part of the Colorado River Basin, the San Juan Mountains on occasion receive heavy daily precipitation amounts which result from storms moving in from the southwest. Many mountain stations in that area can expect daily amounts of precipitation in excess of 1 inch several times each winter. In the higher precipitation areas, precipitation amounts exceeding 1 inch can be expected on the average from 3 to 6 times each winter season. Daily amounts in excess of 2 inches can be expected at some of these stations on an average of to 3 days each winter and occasionally daily amounts in excess of 3 inches are reported. The relative importance of the few days of heavy precipitation is reflected in Figure 35 where it can be noted that slightly over 30% of the total seasonal snowfall occurs on only 10% of the heavier snowfall days. Despite the fact that a few heavy precipitation days occur each year, there are a relatively large number of days with light precipitation. This can also be noted in Figure 35 by observing that 50% of the precipitation days contribute less than 20% of the total snowfall.

To summarize this section on daily snowfall, approximately 50% of the days each winter have snowfall at mountain elevations above 9,000 to 10,000 ft at any one location. Daily precipitation amounts in general are light, with daily averages being under .50 inch on some 80% to 90% of all days. Precipitation amounts in excess of 1 inch can be expected on a few days each winter in the San Juan Mountains and occasionally at the higher precipitation areas in the northern portion of the Basin.

c. Storm duration

The duration of individual storms affects both the planning and operations in a weather modification program. An arbitrary definition has been used to identify storm days, and on this basis, Table XIII has been prepared to show the frequency of storms of different duration. The storm day has been defined as a day on which precipitation of at least .01 inch of precipitation was measured at three or more of the four hourly recording stations in the San Juan area. Using this definition, there were approximately 80 storm periods and 162 storm days in a set of three years' data from November 1964 through May 1967. Since the 7-month, November-May period contains 636 days for the 3-year period, 162 storm days constitute approximately one-fourth of the total 636 elapsed days. Most storm periods are 3 days or less. These include 72 of the 80 storm periods shown in Table XIII. Less important storm days not included in Table XIII indicate there were 47 additional days which had precipitation recorded at only 2 of the 4 stations during the 3 seasons. There were an additional 64 days when precipitation occurred at only one station.

d. The areal extent of precipitation during an episode

General storms producing many hours of precipitation in an area frequently do not have coincident precipitation at stations separated by only a short distance. The hours during which coincident precipitation occurs at 3 or more of the recording stations in the San Juan area constitute less than half of the hours of total precipitation. Ouray, Telluride, and Silverton are less than 20 miles apart in the higher mountainous area and Durango is approximately 40 miles from the other three and to the south of the barrier. Ouray has an upslope

TABLE XI. --Monthly and seasonal precipitation amounts (inches) and number of days during which it fell at hour stations in the Upper Colorado River Basin above Kremmling.

Station	Elevation	November Amt.	November Days	December Amt.	December Days	January Amt.	January Days	February Amt.	February Days	March Amt.	March Days	April Amt.	April Days	May Amt.	May Days	7-Month Totals Amt.	7-Month Totals Days
1964-65																	
Berthoud Pass	11,314	2.87	17	5.64	19	4.47	20	1.95	14	5.60	23	3.28	17	3.25	14	27.06	124
Fraser	8,560	1.36	17	2.47	21	2.52	18	.66	10	2.72	20	1.54	17	1.70	17	12.97	120
Grand Lake 6SSW	8,288	.92	8	2.10	14	1.82	17	.39	10	1.18	18	(.74)	10	1.59	14	8.79	91
Hot Sulphur Springs	7,800	.56	3	1.82	10	1.31	8	.28	3	1.47	10	.48	4	1.38	10	7.30	48
1965-66																	
Berthoud Pass		3.94	18	1.65	11	1.42	12	2.65	21	1.62	9	3.41	16	1.60	12	16.29	99
Fraser		2.40	13	.90	10	.67	9	.89	14	.57	7	1.23	10	1.21	10	7.87	73
Grand Lake 6SSW		2.26	13	.45	11	.38	12	.43	15	.44	6	1.10	10	.91	12	5.97	79
Hot Sulphur Springs		1.39	8	.82	4	.12	2	.35	4	.36	1	.90	5	.60	5	4.54	29
1966-67																	
Berthoud Pass		1.84	11	2.66	14	3.80	17	4.29	19	2.91	17	3.73	12	3.82	18	23.05	108
Fraser		.75	7	1.69	12	1.85	18	3.24	15	1.80	11	2.00	10	1.90	17	13.23	90
Grand Lake 6SSW		.52	8	1.76	11	.31	18	1.07	16	1.41	11	1.01	10	.70	11	7.78	85
Hot Sulphur Springs		.23	1	1.84	6	.75	6	1.29	8	.92	9	.59	5	1.15	6	6.77	41

Three - Season Totals	Station	Amt.	Days	Ave. / Day
	Berthoud Pass	66.40	331	.20
	Fraser	34.07	283	.13
	Grand Lake 6SSW	22.54	255	.09
	Hot Sulphur Springs	18.61	118	.16

TABLE XII. --Three-season historical record of daily precipitation amounts at Berthoud Pass which equaled or exceeded .40 inch.

BERTHOUD PASS DAYS ≥ .40

1964-65

November	.45	.49					
December	.54	.42	1.23	.79	.45	.63	
January	.59	1.03					
February	.65						
March	.41	.55	.62	.54			
April	.58	.40					
May	.48	.71	.41				11.97 on 20 days

1965-66

November	.79	.45	.40	.86	
December	.41				
January	0				
February	.44				
March	.40				
April	.50	.45			
May	.55				5.25 on 10 days

1966-67

November	.69			
December	1.03	.79		
January	.59	.48	.59	
February	.42	.78	.52	
March	.65			
April	1.27	.46		
May	.60	.71		9.58 on 14 days

TABLE XIII. --Three season totals of storm days grouped by duration periods, San Juan area.

Duration	1 day	2 days	3 days	4 days	6 days	8 days	Total
Number Cases	34	26	12	5	2	1	80
Number Days	34	52	36	20	12	8	162

exposure from the north. Table XIV, for example, shows the coincident amounts of precipitation at the respective stations hour by hour for the period 27-29 December 1964. This is presented as a typical case to show the correspondence of precipitation for the respective hours and is typical of some of the heavier storms in the San Juan area. In this particular sequence, there were 32 hours that had precipitation at one or more stations. Slightly more than half of these (17 hours) had coincident precipitation at two or more stations. A quarter of these (8 hours) had coincident precipitation at three or more stations and only four hours had simulataneous precipitation at all four stations. During the hours shown with an "X" for Telluride, the gage was only accumulating precipitation and not giving hourly amounts. These hours have not been counted in the above tabulation, but are shown since this is frequently the case for hourly precipitation data reported in the publication "Climatological Data." Precipitation at any individual station is highly dependent upon its orographic exposure at any specific time, and it cannot be assumed that snowfall is occurring simultaneously at all areas during precipitation episodes. This substantially increases the number of hours of precipitation that must be

TABLE XIV--Hourly precipitation, December 27 - 29, 1964 (hundredths of an inch).

Hour of Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Dec. 27																								
Ouray																				3	3	4		
Telluride																			9	7	7	4	2	8
Silverton		2								2		4	2	3	3	4	8	5	9	7	7	10	2	6
Durango	6	6	3			2	3		2	2						4	4	4	3	7	5	2	8	1
Dec. 28																								
Ouray		2	4	7	6			2									2							
Telluride				6	2														X	X	X	X	X	X
Silverton	3		3	2		2											2		3	4				4
Durango	5	12	9	2																				
Dec. 29																								
Ouray		2			3	5																		
Telluride	X	X	X	X	X	X																		
Silverton																								
Durango	2	3																						

TABLE XV. --Matrix of partial correlation coefficients of 9 stations located in the northern and central Colorado Rockies. Sample consists of 545 daily precipitation amounts for the period November - April.

	Climax	Aspen	Crested Butte	Eagle	Fraser	Marvine	Shoshone	Winter Park	Grand Lake 6SSW
Climax	1.000	.615	.573	.340	.500	.381	.387	.733	.005
Aspen		1.000	.730	.399	.363	.470	.538	.478	.023
Crested Butte			1.000	.437	.361	.481	.561	.423	.026
Eagle				1.000	.188	.383	.519	.213	-.012
Fraser					1.000	.258	.299	.611	.044
Marvine						1.000	.453	.305	.051
Shoshone							1.000	.338	.110
Winter Park								1.000	.089
Grand Lake 6SSW									1.000

considered for weather modification efforts above the value that would be estimated from single stations.

The homogeneity of precipitation over sub-areas of the Colorado River Basin can also be shown by the correlation between stations. Correlation matrices for a group of stations in the Upper Basin is shown in Table XV and a matrix for the San Juan area is shown in Table XVI. It can be noted that the best correlations of daily precipitation are generally around .7 to .8. Most values are considerably lower. This is a reflection of the different elevations and exposures of the respective stations where historical records exist. Tables XVII and XVIII, respectively, show multiple correlations between Climax and other northern stations, and between Wolf Creek summit and other San Juan stations. It can be noted that such multiple correlations explain something over 60% of the variability in the northern areas and something over 50% in the San Juan area.

TABLE XVI. --Matrix of partial correlation coefficients of 14 stations located in southern Colorado and extreme northern New Mexico. Sample consists of 379 daily precipitation amounts for the period November - April.

	W. C. Summit	Durango	Ft. Lewis	Ignacio	Mancos	Mesa Verde	Ouray	Placerville	Powderhorn	Rico	Telluride	Farmington N. M.	Bloomfield	Dulce N. M.
W. C. Summit	1.000	.668	.646	.409	.496	.601	.501	.253	.396	.529	.556	.391	.374	.153
Durango		1.000	.842	.609	.600	.813	.427	.183	.329	.753	.549	.653	.566	.201
Ft. Lewis			1.000	.454	.606	.803	.426	.220	.316	.675	.487	.567	.501	.207
Ignacio				1.000	.460	.543	.254	.081	.198	.442	.324	.433	.508	.249
Mancos					1.000	.853	.590	.366	.471	.590	.638	.517	.475	.170
Mesa Verde						1.000	.521	.316	.398	.702	.563	.692	.604	.215
Ouray							1.000	.428	.518	.493	.747	.346	.380	.124
Placerville								1.000	.350	.305	.387	.131	.354	.033
Powderhorn									1.000	.313	.563	.265	.288	.124
Rico										1.000	.562	.510	.345	.113
Telluride											1.000	.410	.376	.113
Farmington, N. M.												1.000	.636	.342
Bloomfield													1.000	.204
Dulce, N. M.														1.000

TABLE XVII. --Climax stepwise multiple correlation coefficients and variances explained by 8 stations located over the northern and central Colorado Rockies. Sample consists of 545 daily precipitation amounts for the period November - April.

	Multiple Corr.	Total Variance Explained	Increment of Explained Variance
Winter Park	.7332	.5375	.5375
Aspen	.7926	.6282	.0907
Crested Butte	.8019	.6430	.0147
Eagle	.8043	.6469	.0039
Grand Lake 6SSW	.8060	.6496	.0027
Shoshone	.8070	.6513	.0017
Fraser	.8074	.6518	.0006
Marvine	.8077	.6523	.0005

TABLE XVIII. --Wolf Creek Summit stepwise multiple correlation coefficients and variances explained by 13 stations located over southern Colorado and extreme northern New Mexico. Sample consists of 379 daily precipitation days for period November - April.

	Multiple Correlation	Total Variance Explained	Increment of Explained Variance
Durango	.6684	.4468	.4468
Ouray	.7096	.5036	.0568
Fort Lewis	.7201	.5185	.0150
Telluride	.7262	.5274	.0089
Farmington, N. M.	.7317	.5354	.0080
Powderhorn	.7347	.5398	.0045
Rico	.7363	.5421	.0023
Bloomfield	.7369	.5430	.0009
Ignacio	.7378	.5444	.0014
Placerville	.7387	.5456	.0012
Mancos	.7395	.5468	.0012
Mesa Verde	.7406	.5485	.0017
Dulce, N. M.	.7408	.5487	.0002

e. Diurnal patterns of temperature during periods of precipitation

If the precipitation mechanism within the cloud mass is subject to strong variations based on temperature, the daily fluctuation in temperature at high elevation stations may furnish some indication of the corresponding temperature change taking place within the clouds only a few hundred feet higher.

A study has been made of the relationship between daily temperatures as shown by maximum and minimum temperatures at Jones Pass, Sugarloaf Reservoir, Leadville, and Berthoud Pass with the hourly precipitation at Climax. The seven-month daily average range of temperatures between minimum and maximum, at these mountain stations, November through May, is from 20° to 29° F. This includes the daily range on both clear and cloudy days. Although snowy days have considerably less temperature range than clear days, daily temperature fluctuations between 10° and 15° were quite common even during times of precipitation.

Figure 35 illustrates daily temperature ranges which prevailed under continuous heavy precipitation conditions at Climax. Only diffuse solar radiation would have been possible at the earth's

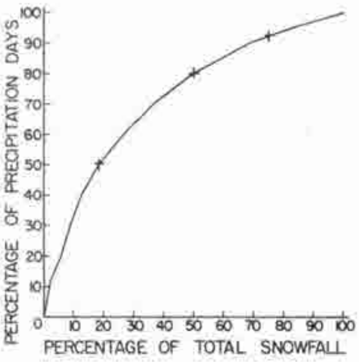


Figure 35. --Wolf Creek Summit daily distribution of snowfall, November 1958 - April 1968 (November - April).

surface through the continuous cloud cover. On the three days shown in Figure 36, the daily temperature ranges were 9°, 10°, and 6°, respectively. Since these temperatures are observed at 11,300 ft during a time when the vertical temperature distribution, both in and beneath the cloud should be near the saturation lapse rate, it is quite probable that a daily variation of up to 10° is taking place in the lower portion of the cloud.

f. Variability of snow accumulation

The highest total cumulative snow depth as usually measured by the Soil Conservation Service occurs in their April 1 reading. Determination of the variability of the April 1 reading has been made for the different sub-areas of the Colorado River Basin.

The four snow courses in the Grand Mesa area show the lowest variability. This indicates that this area not only consistently receives large amounts of snow each year but it does so with regularity. The highest variability occurs in the snow courses that are on the eastern slopes of the Rocky Mountains and other mountainous areas which are located downwind from higher terrain.

g. Summary comments on the surface climatology

The predominant characteristics of wintertime storms in the Colorado Rockies can be summarized as follows:

Precipitation occurs on nearly half the days, November through May at elevations above 10,000 ft.

Most daily precipitation amounts are less than .3 inch per day.

Precipitation occurs at about half the stations during about half the hours when precipitation is occurring over a given region.

Storm periods lasting three or more consecutive days are normally less frequent than one per month.

In the San Juan area precipitation usually begins in the mountain areas, expands upwind to the lower elevations, and generally ends last at Ouray on the northern slopes. This is probably due to the favorable orographic effect produced by the northwesterly airflow which exists after the frontal or trough passage.

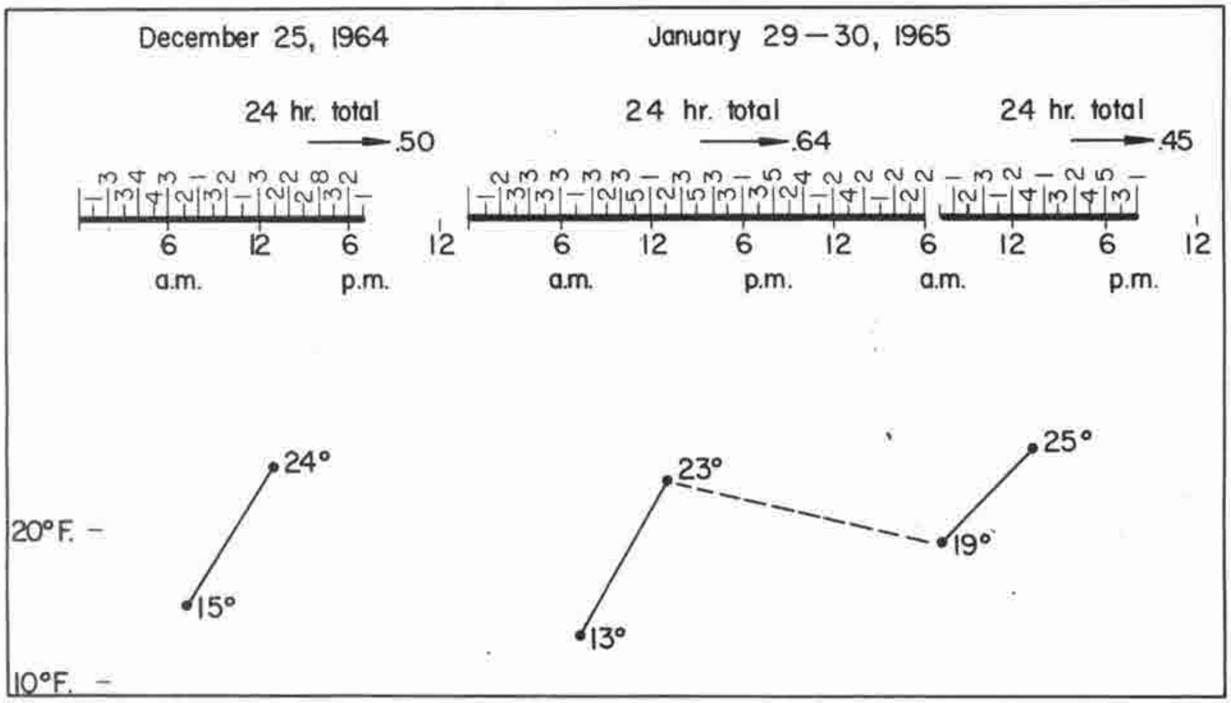


Figure 36. --Examples of daily temperature range during continuous cloud cover and snow at Climax 2NW.

In the northern Colorado River Basin, there is a substantial daily peak in both frequency and amount of precipitation between midnight and 6 a.m.

Daily temperature fluctuations at the higher mountain areas is frequently as great as 10° F even on days of heavy snowfall.

2. Upper Air Climatology

a. Upper air climatology as related to daily snowfall events

An upper air climatology of natural daily snowfall has been prepared for Climax, Colorado, utilizing the non-seeded days of the randomized experiment between 1960-65 and for the San Juan Mountains using the unseeded winter seasons of 1965-66 and 1967-68. This study considers the frequency of occurrence and contributions to the total snowfall within various classes through the range of the meteorological variables. The parameters chosen for this investigation are related to orographic influences, available moisture supply, air mass stability, and cloud system temperatures. The variation of the mean daily snowfall is also determined as a function of the meteorological parameters.

(1) Daily snowfall related to cloud top temperatures

Figure 37 shows the natural mean daily snowfall as a function of cloud top temperatures (500 mb) for Climax, Colorado. The lower diagram (b) is constructed by utilizing a running mean containing a two-degree interval of temperature while the top diagram (a) consists of a mean computed over a four-degree class interval.

A peak in the mean daily snowfall appears in the -21° C to -24° C class interval while the running mean indicates a peak around -20° C to -21° C. Daily snowfall decreases at both colder and warmer cloud top temperatures. The decrease of mean daily snowfall at the colder cloud temperatures follows very nearly the trend of the potential condensate in the 700 - 500 mb layer. At the warmer cloud temperatures, however, the decrease in snowfall above -20° C is quite marked and occurs in spite of the increase in potential condensate

A small secondary peak is noted in the mean daily snowfall around -14° C to -15° C (Figure 37, diagram a).

The histograms of Figure 38 show how the total snowfall and the total occurrences are distributed with respect to the 500 mb temperatures. The histograms are generated utilizing 4-degree class intervals. It is seen that about 42% of the total snowfall and 35% of the total occurrences are contained in the class interval from -20.5° C to -24.5° C.

Figure 39 shows the natural mean daily snowfall as a function of cloud top temperature (500 mb) for the pooled Wolf Creek Summit and Wolf Creek West recording gages. The lower diagram (b) again is constructed utilizing a running mean containing a two-degree interval of temperature while the top diagram (a) consists of a mean computed over a four-degree class interval.

A peak in the mean daily snowfall is evident at around -23° C. As cloud temperatures become colder the average snowfall decreases

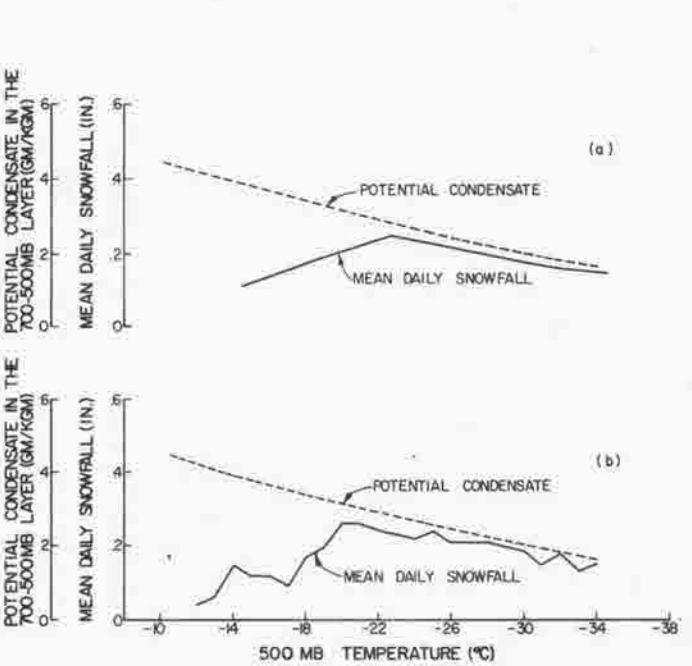


Figure 37. --Solid Lines: Mean Daily **Snowfall** at Climax, Colorado, as a function of the cloud top temperature (500 mb). Dashed Line: Adiabatic condensate realized from lifting a parcel upward through a saturated 700-500 mb layer.

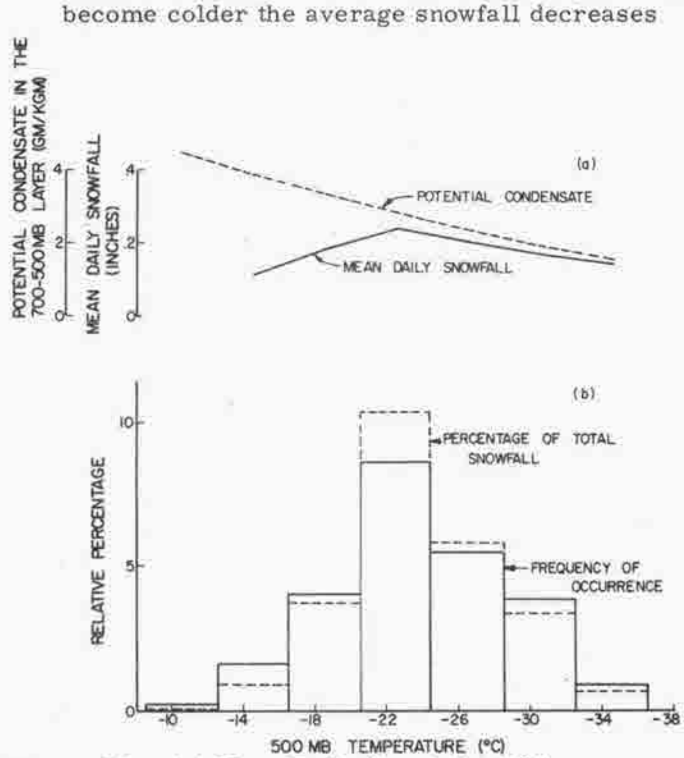


Figure 38. --(a) Mean Daily Snowfall at Climax as a function of cloud top temperature (500 mb).
(b) Distributions of total snowfall and total occurrences as a function of cloud top temperature (500 mb).

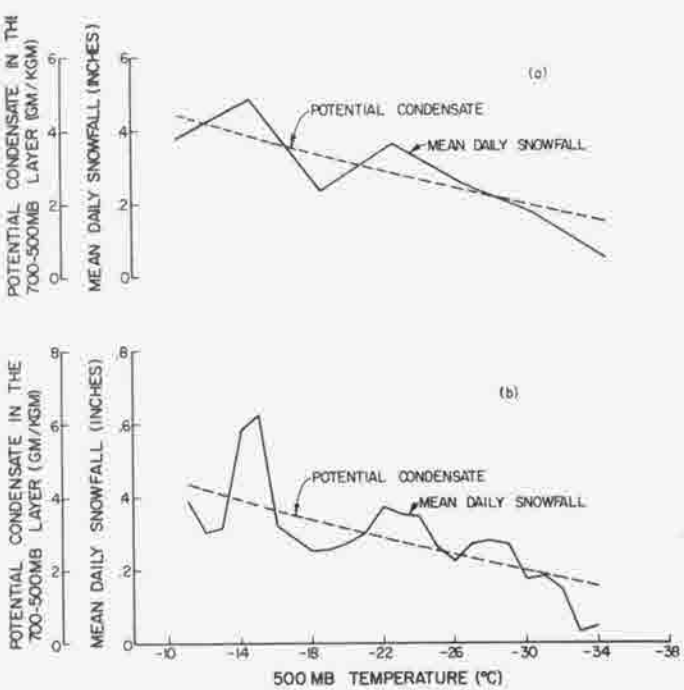


Figure 39. --Solid Lines: Mean Daily Snowfall at Wolf Creek Pass as a function of cloud top temperatures (500 mb). Dashed Lines: Adiabatic condensate realized from lifting a parcel upward through a saturated 700-500 mb layer.

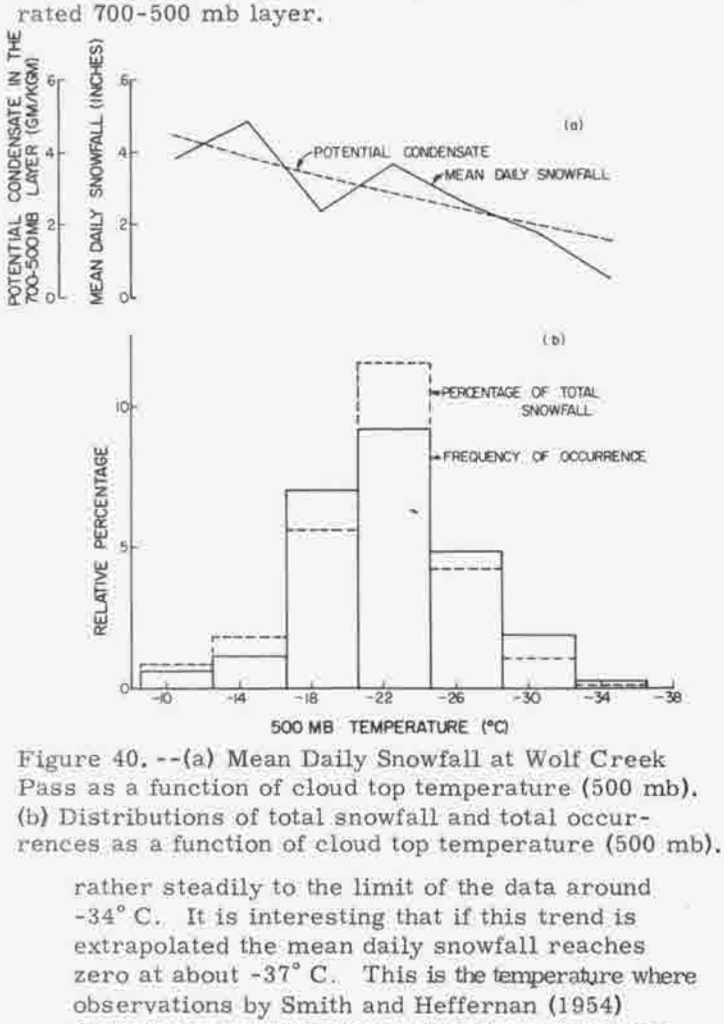


Figure 40. --(a) Mean Daily Snowfall at Wolf Creek Pass as a function of cloud top temperature (500 mb). (b) Distributions of total snowfall and total occurrences as a function of cloud top temperature (500 mb).

rather steadily to the limit of the data around -34° C. It is interesting that if this trend is extrapolated the mean daily snowfall reaches zero at about -37° C. This is the temperature where observations by Smith and Heffernan (1954) indicate concentrations of effective natural ice nuclei are approximately equal to cloud droplet concentrations. As a consequence, immediate icing of the cloud would result in cessation of the precipitation process.

The decrease in mean snowfall as cloud top temperatures become colder than -23° C is largely explained by the decrease of potential condensate in the cloud system. This is illustrated in Figure 39 by the dashed lines which reflect the amount of adiabatic condensate produced by a parcel moving upward through a 700-500 mb saturated layer as a function of the 500 mb temperature.

The peak in mean daily snowfall at -23° C appears to reflect a cloud top temperature mode where the condensation supply and available effective ice nuclei maximize the precipitation process.

The decrease of mean daily snowfall as cloud top temperatures become warmer is quite intriguing. The mean daily snowfall decreases steadily from -23° C to a minimum about -18° C. This occurs in spite of an increase in potential condensate for these cloud systems. This decrease cannot be explained by a lessening of any orographic influence since an increase in southwesterly flow events and increasing wind speeds occur within this temperature range. It appears the natural precipitation process is becoming increasingly inefficient as temperatures decrease from -23° C to -18° C probably due to the accompanying exponential decrease of available effective ice nuclei.

The marked increase of mean daily snowfall at Wolf Creek Pass for 500 mb temperatures around -14° C to -15° C is striking. However, since this occurs near the tail of the distribution, sample sizes are relatively small. Possible explanations for this peak do exist. One possibility is that this is the range of temperature where dendritic crystal habits might be expected to form in the upper portion of the cloud system. This could result in fracturing of the dendritic crystals and an ice crystal multiplication process in the cloud system. This should cause an increase in the natural efficiency of cloud water removal and therefore in observed precipitation. Whatever the mechanism for this increase in natural snowfall efficiency at Wolf Creek Pass, it apparently occurs less frequently at Climax. Figure 37 indicates only a minor peak in mean daily snowfall at Climax at these temperatures.

It is interesting that the mean daily snowfall appears to decrease again at the warmest cloud top temperatures contained in the data (-11° C to -13° C). However, with the limited sample sizes involved this is only conjecture.

Figure 40 shows how the total snowfall and the total occurrences are distributed with respect to the 500 mb temperature. It is seen that 46% of the total snowfall and 37% of the total occurrences are contained in the class interval from -20.5° C to -24.5° C. The 9% excess of the relative snowfall percentage over the relative frequency in this class reflects the increased daily snowfall under these conditions. A decrease of daily snowfall to below the overall average is indicated for the temperature class from from -16.5° C to -20.5° C, as well as for all colder temperature classes.

(2) Daily snowfall related to upper level airflow

Figure 41 shows the distribution of snowfall and occurrences at Climax as a function of the 700 mb wind direction. The distributions are determined by utilizing 20 degree class intervals for the wind direction.

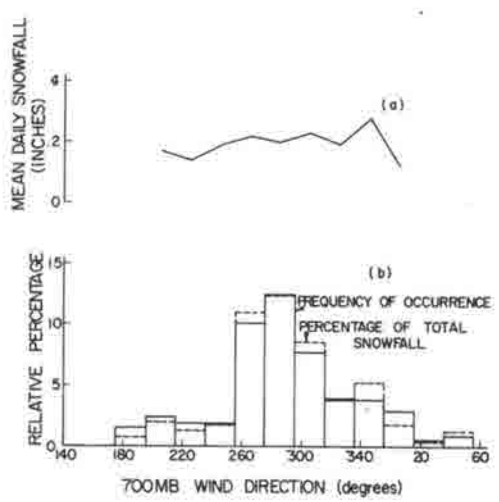


Figure 41. --(a) Mean Daily Snowfall at Climax as a function of the 700 mb wind direction. (b) Distributions of total snowfall and total occurrences as a function of the 700 mb wind direction computed over 20 degree class intervals.

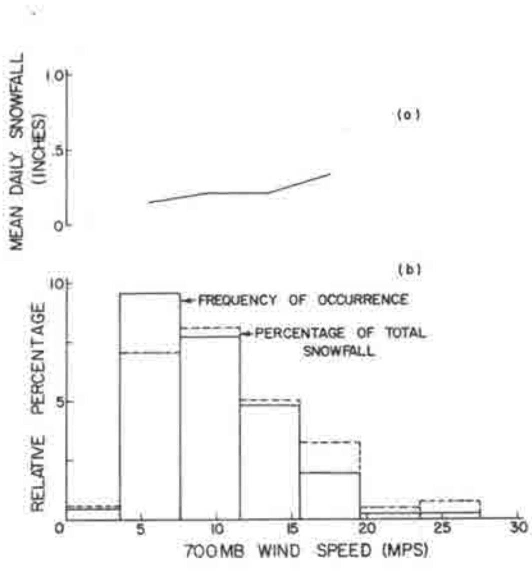


Figure 42. --(a) Mean Daily Snowfall at Climax as a function of the 700 mb wind speed. (b) Distributions of total snowfall and total occurrences as a function of the 700 mb wind speed computed over 4 mps class intervals.

The greatest frequency of daily snowfall and the main contribution to total snowfall occurs in the 280-290 degree class interval. It is quite evident that snowfall is more frequent and heavier with northwest flow at Climax. About 50% of the total snow occurs with the 700 mb wind between 280 and 330 degrees while only about 12% of the total snow occurs with the flow from 180 to 250 degrees. The lack of snowfall with southwest flow is apparently due to the presence of two major mountain massifs to the southwest of Climax. These are the San Juan Mountains and the Sawatch Range. The greater frequency and larger snowfalls with northwest flow at Climax attest to the pronounced orographic influence on wintertime precipitation since this type of flow exists after the upper trough has passed the area, and the stronger synoptic scale upward motions are well to the east.

Figure 42 shows the distribution of natural snowfall and occurrences at Climax as a function of the 700 mb wind speed computed using 4 mps class intervals. The relative percentage of the total snowfall is higher than the relative frequency for the higher wind speeds suggesting again an orographic influence on the precipitation. A slight increase of the mean daily snowfall with wind speed above 6 mps is noted for the Climax area.

Figure 43 shows the distribution of natural snowfall at Wolf Creek Summit during the two unseeded winter seasons as a function of the 700 mb wind direction. The distributions are determined by utilizing 20 degree class intervals for the wind direction. The frequency of occurrence of daily snowfall is also included. It is readily apparent that the occurrences of snowfall are distributed nearly symmetrical about the prevailing westerlies, indicating that the migrating disturbances in the mean westerly flow play an important part in determining the occurrence frequency. Snowfall amounts, on the other hand, are highly skewed toward southwest flow, a direction normal to the mountain barrier. This indicates that the mean daily snowfall is a maximum under southwest flow conditions where favorable orographic effects are superimposed upon the stronger synoptic scale upward motions.

Wind flow at 700 mb from 180° to 270° accounts for 81% of the total snowfall on Wolf Creek Summit but represents only 53% of the total occurrences. Wind flow from 280° to 350° represents 37% of the total occurrences but contributes only 16% of the total snowfall.

The influence of the orography upon the mean daily snowfall is striking. Northwest and northerly flow snowfall generally averages around 0.10 inch per day (water equivalent) or less, while south and southwesterly flow snowfall averages in excess of 0.50 inch per day (water equivalent). Snowfall occurring with the 700 mb wind flow within 25° to a normal to the mountain barrier accounts for 60.5% of the total snowfall.

The orographic influence on snowfall at Wolf Creek Summit is also strongly reflected by the 700 mb wind speed. This is shown in Figure 44. The distributions were computed using 4 mps class intervals. It is readily apparent from the distributions of snowfall frequency and amounts that much more snow is

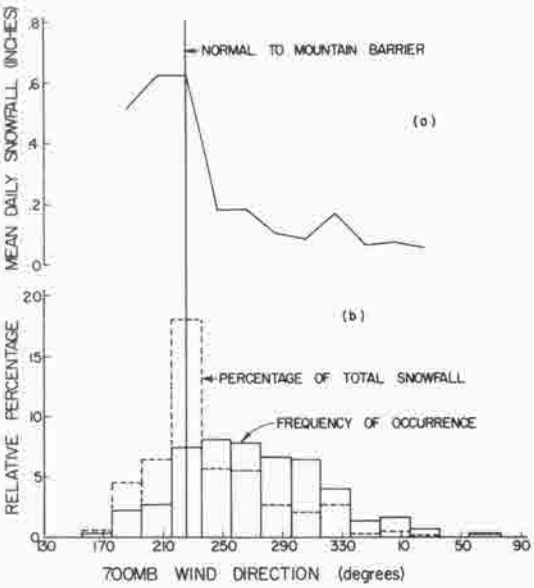


Figure 43.--(a) Mean Daily Snowfall at Wolf Creek Summit as a function of 700 mb wind direction. (b) Distributions of total snowfall and total occurrences as a function of the 700 mb wind direction computed over a 20-degree class interval.

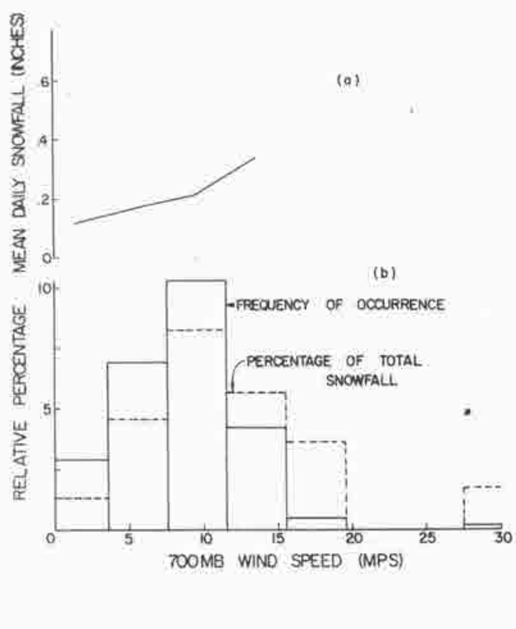


Figure 44.--(a) Mean Daily Snowfall at Wolf Creek Summit as a function of the 700 mb wind speed. (b) Distribution of total snowfall and total occurrences as a function of the 700 mb wind speed computed over a 4 mps class interval.

realized per occurrence at the higher wind speeds.

The class interval from 7.5 to 11.5 mps contains the peak in the frequency of occurrence and also in total snowfall. However, substantial quantities of snow are realized from a few occurrences at wind speeds of 16 mps and greater. This is indicated most spectacularly by the mean daily snowfall. In the 15.5 to 19.5 mps class interval three storms averaged over 1.8 inches per day (water equivalent) while one storm having wind speeds of around 29 mps produced 2.6 inches per day. The cases having wind speeds of 15.5 mps or greater represent only about 3% of the total cases but contribute over 21% of the total snowfall.

Since the rate of condensation production is only a linear function of the vertical motion, a more linear relationship between mean daily snowfall and the speed of the wind over the mountain barrier might be expected. This relation appears to hold for wind speeds below about 10 mps, but above this value indications are that some favorable combination of factors is increasing the snowfall. This may be due to the superposition of the orographic influence upon strong synoptic scale upward motions at the higher wind speeds. Also, increased low level convergence forced by the concavity of the terrain may account for part of the non-linearity.

(3) Daily snowfall related to moisture supply

The 700 mb mixing ratio is a good measure of the moisture supply contained in the air mass that will be lifted over the mountain barrier. Figure 45 shows the distribution of snowfall occurrences and amounts as a function of this variable computed using 0.4 gm/kgm class intervals.

It is apparent that the center of mass of the frequency distribution is displaced substantially toward lower moisture values from the center of mass of the snowfall distribution. The centers are found at 1.95 gm/kgm and 2.17 gm/kgm, respectively. Thus, the larger daily snowfalls occur in association with the higher 700 mb mixing ratios as would be expected.

Figure 46 shows the distribution of snowfall occurrences and quantity as a function of this variable computed using 0.4 gm/kgm class intervals for Wolf Creek Summit.

It is immediately apparent that the center of mass of the total snowfall distribution is displaced substantially toward higher moisture values from the center of mass of the frequency distribution. The centers are found at 2.5 gm/kgm and 2.1 gm/kgm, respectively. Thus, the larger daily snowfalls occur in association with the higher 700 mb mixing ratios as would be expected. These center of mass values are higher than those observed at Climax indicating more moisture is present on the average at Wolf Creek Pass.

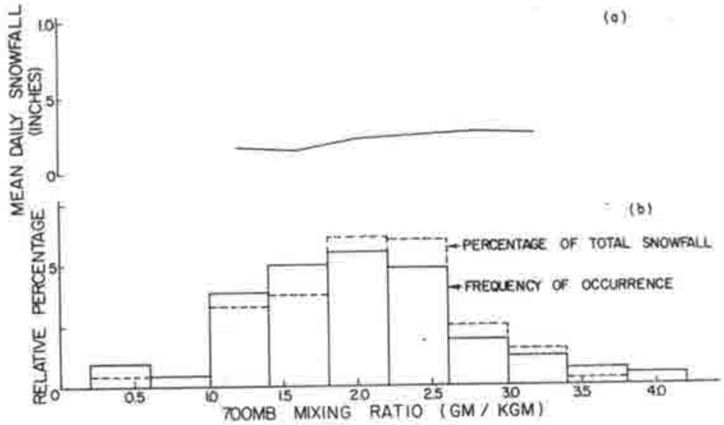


Figure 45. --(a) Mean Daily Snowfall at Climax as a function of the 700 mb mixing ratio. (b) Distribution of total snowfall and total occurrences as a function of the 700 mb mixing ratio computed over a . 4 gm/kgm class interval.

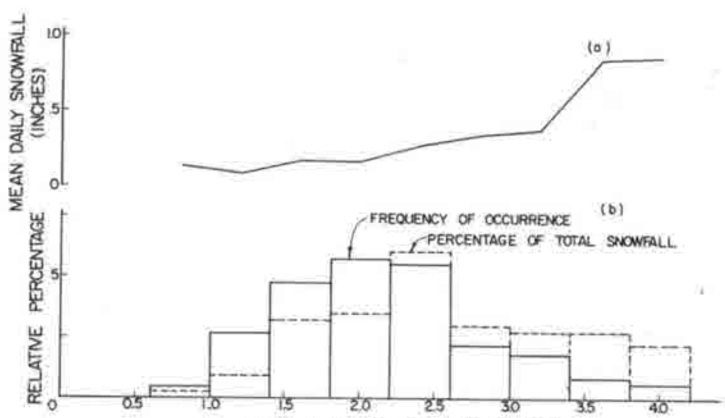


Figure 46. --(a) Mean Daily Snowfall at Wolf Creek Summit as a function of 700 mb mixing ratio. (b) Distribution of total snowfall and total occurrences as a function of the 700 mb mixing ratio computed over a . 4 gm/kgm class interval.

The distribution of mean daily snowfall shown in Figure 46 exhibits a trend upward with the mixing ratio. The trend is nearly linear up to 3. 2 gm/kgm but a sharp increase is noted between 3. 2 gm/kgm and 3. 6 gm/kgm.

(4) Daily snowfall related to equivalent potential temperature

At Climax, Colorado, the 700 mb level is generally just below cloud base. The equivalent potential temperature at this level then very nearly defines the pseudoadiabatic process curve taken by air parcels participating in the precipitation process.

Figure 47 shows the distribution of snowfall and daily snowfall occurrences as a function of the 700 mb equivalent potential temperature computed using a 4° K class interval. The frequency curve indicates a broad maximum

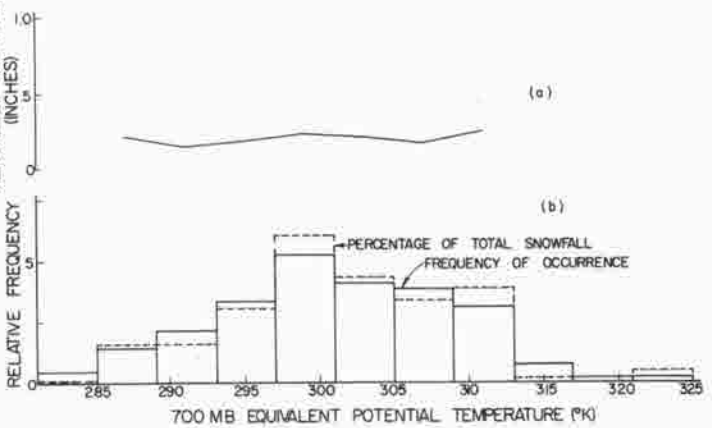


Figure 47. --(a) Mean Daily Snowfall at Climax as a function of the 700 mb equivalent potential temperature. (b) Distribution of total snowfall and total occurrences as a function of the 700 mb equivalent potential temperature computed over a 4-degree class interval.

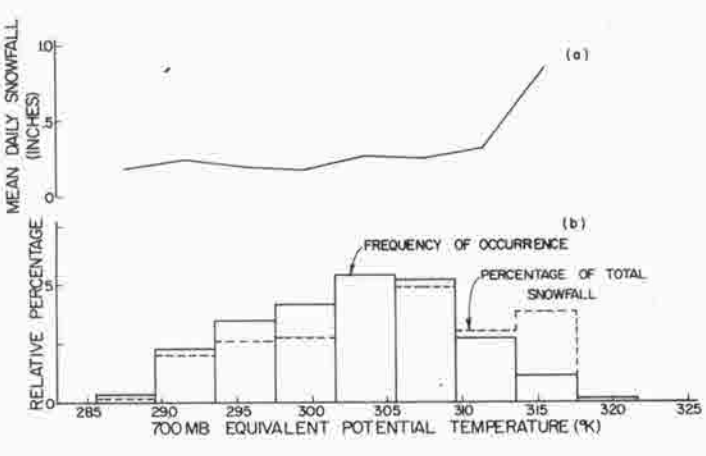


Figure 48. --(a) Mean Daily Snowfall at Wolf Creek Summit as a function of 700 mb equivalent potential temperature. (b) Distribution of total snowfall and total occurrences as a function of the 700 mb equivalent potential temperature computed over a 4-degree class interval.

between 297° K and 309° K which contains 53% of a all occurrences. The center of mass is at about 301° K.

An interesting bi-modal distribution is seen in the snowfall curve with peaks at 299° K and 311° K.

The mean daily snowfall curve is relatively flat indicating that the equivalent potential temperature explains very little of the variation in the daily snowfall. This is difficult to reconcile since the adiabatic condensate increases with the equivalent potential temperature, all other effects being equal. It appears that any increase in precipitation that might result from the increased condensate associated with warmer equivalent potential temperatures is negated by an increase in the inefficiency of the cloud system to convert the added condensate to precipitation. This may be due to a growing lack of effective ice nuclei in the warmer cloud systems below that which is required to utilize the additional cloud water produced.

Figure 48 shows the distribution of snowfall and daily snowfall occurrences as a function of the 700 mb equivalent potential temperature computed using 4° K class intervals. The frequency curve indicates a broad maximum in occurrence between 301.5° K and 309.5° K with snowfall occurrences noted over a range extending from about 283° K to 321° K.

An interesting bi-modal distribution is apparent in the snowfall curve. The major snowfall occurs coincident with the occurrence maximum between 301.5° K and 309.5° K. However, a second peak is noted from 313.5° K to 317.5° K indicating the presence of a separate population of relatively infrequent but quite heavy daily snowfalls. This bi-modal distribution in snowfall is similar to that observed at Climax although the peaks occur at somewhat warmer temperatures.

Mean daily snowfalls average about 0.2 inch water equivalent for equivalent potential temperatures up to about 301.5° K. A gradual increase in mean daily snowfall is observed up to 311.5° K followed by an abrupt increase thereafter. This abrupt upward swing in the mean daily snowfall again appears to reflect a favorable combination of factors since it cannot be totally explained by the variation of the equivalent potential temperature.

(5) Daily snowfall related to stability

The vertical variation of equivalent potential temperature may be used to define a stability for moist processes. An index is derived by subtracting the equivalent potential temperature at 700 mb from the value at 500 mb. Figure 49 shows the distributions of snowfall occurrence and snowfall at Climax as a function of this moist stability index computed for 2° K class intervals.

It is seen that only 4.2% of the total snowfall occurs under unstable conditions and 67% with an index between 0 and +6.

The mean daily snowfall reaches a peak in the class interval from +2 to +4.

Figure 50 shows the distributions of snowfall occurrence and snowfall as a function of this index computed using 2° K class intervals.

About 70% of snowfall occurrences producing over 77% of the total snowfall occurs with values of the stability index between +0.5 and +6.5. Less than 7% of the total occurrence are associated with unstable conditions and these produce less than 5% of the total snowfall.

The mean daily snowfall reaches a peak in the class from +2.5 to +4.5 similar to that observed at Climax.

(6) Summary

Orographic influences at Climax result in greater amounts of snowfall with northwest flow and a damping of snowfall activity when southwest flow is present. The

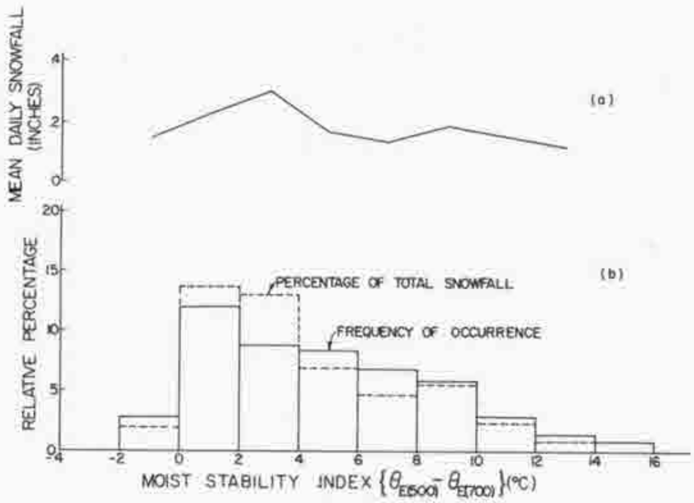


Figure 49.--(a) Mean Daily Snowfall at Climax as a function of a moist stability index. (b) Distribution of total snowfall and total occurrences as a function of a moist stability index computed over a 2-degree class interval.

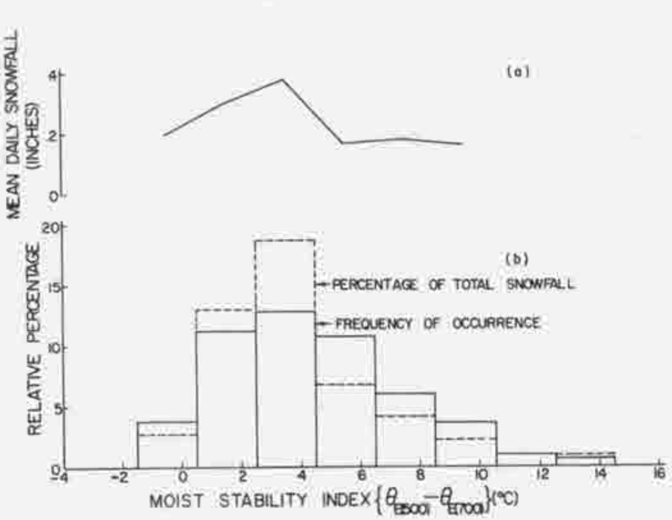


Figure 50. --(a) Mean Daily Snowfall at Wolf Creek Summit as a function of a moist stability index. (b) Distribution of total snowfall and total occurrences as a function of a moist stability index computed over a 2 degree class interval.

orographic effect at Climax appears less pronounced than at Wolf Creek Summit. Snowfall at Climax occurs from cloud systems that average slightly colder and drier than those observed at Wolf Creek Pass.

The most interesting contrast between the Climax and Wolf Creek Pass daily snowfall climatology is the lack of the marked peak in snowfall at around -14° C to -15° C. The very heavy daily snowfalls observed at Wolf Creek Pass (1.25 water equivalent or more) are nearly non-existent in the Climax area.

The occurrence of daily snowfall on Wolf Creek Pass appears to be controlled by the presence of disturbances in the prevailing westerlies during the winter season. The quantity of snowfall per day, however, is mainly controlled by a combination of the orographic features of the area, available moisture supply, and synoptic scale upward motions. There are strong indications that the natural snowfall process becomes relatively inefficient for cloud top temperatures warmer than -22° C except for around -14° C to -15° C where there is some evidence of possible ice crystal multiplication processes. It appears that the wind speed, wind direction, moisture supply, cloud system temperatures, and synoptic scale upward motions combine to produce rather infrequent but very heavy daily snowfalls.

b. Upper Air Climatology Related to Excess Snowfalls at Wolf Creek Pass

An upper air climatology of excessive daily snowfall at Wolf Creek Pass was determined for the 4-year period 1964-68. Daily snowfalls containing 1.20 inches water equivalent or more at Wolf Creek West and/or Wolf Creek Summit recording gages were chosen for the study. Seeded and non-seeded events were investigated separately and then combined into a single sample. Table XIX shows the results of this investigation.

A large orographic influence in the production of these heavy snow episodes is readily apparent. The 700 mb wind speed averages about 16.5 mps (32 knots) for the seeded and unseeded heavy snow events, while the 500 mb wind speed averages nearly 28 mps (55 knots). The strong orographic effect is also demonstrated in the prevailing wind direction during these heavy snow events. The 700 mb wind direction associated with these excessive snows ranges from 180° to 260°, averaging 220° for the unseeded cases and 239° for the seeded events. An azimuth perpendicular to the San Juan Mountain barrier at Wolf Creek Pass lies at an angle of 225°. Therefore, all events have 700 mb wind directions within 45° of the normal to the barrier.

The 500 mb wind direction exhibits similar characteristics. It ranges from 190° to 280° during all events averaging 230° for the unseeded cases and 237° for the seeded episodes.

The turning of the wind with height indicates that excessive snowfall is generally associated with neutral or warm advection in the 700-500 mb layer. Table XIX shows only one case where slight cold advection was occurring in this layer. The average warm advection computed for seeded and non-seeded cases amounts to approximately 2° C per 12 hours and 3° C per 12 hours, respectively.

TABLE XIX. --Upper level meteorological parameters associated with excessive daily snowfall on Wolf Creek Pass. Storm events have produced 1.20 inches water equivalent per 24 hours at Wolf Creek West and/or Wolf Creek Summit.

Date	W.C. West Daily Precip. (Inches)	W.C. Summit Daily Precip. (Inches)	700 mb Wind Direction (Degrees)	500 mb Wind Direction (Degrees)	700 mb Wind Speed (MPS)	500 mb Wind Speed (MPS)	700 mb Mixing Ratio (GM/KGM)	700 mb Equiv. Pot. Temp. (°K)	500 mb Temp. (°C)	Mean Temp. Advection (°C/12 hr)	Convective Instability (°C)
(Unseeded)											
11-25-65	1.60	M	250	250	19	32	3.93	316.8	-15	0.	2.7
12-23-65	M	2.27	210	220	13	25	4.04	313.9	-18	2.3	1.5
12-30-65	M	2.60	220	230	28	32	3.73	316.2	-15	6.4	2.8
12-16-67	1.34	1.24	180	190	13	28	3.73	310.7	-18	2.6	3.9
12-19-67	1.97	1.65	220	240	18	28	2.43	304.8	-22	7.1	3.9
12-20-67	2.11	2.10	220	220	17	28	3.00	306.4	-21	0	3.5
1-28-68	1.43	1.76	220	230	19	31	2.73	307.9	-21	4.2	1.1
2-13-68	1.41	.84	240	260	5	15	2.26	298.8	-23	1.1	8.4
Average	1.64	1.78	220	230	16.5	27.4	3.23	309.4	-19.1	2.9	3.5
(Seeded)											
12-28-64	M	2.40	250	260	18	29	2.84	310.4	-18	3.7	4.6
1-7-65	3.05	2.39	230	230	9	32	3.60	312.6	-13	0	10.4
1-8-65	1.52	.98	230	230	17	32	2.99	311.9	-18	0	1.5
4-10-65	1.20	.74	220	230	17	23	2.62	309.7	-21	2.8	-1.0
12-6-66	2.43	3.03	260	280	22	29	4.42	317.1	-12	8.9	7.4
12-7-66	2.40	2.13	240	250	16	27	4.61	318.8	-14	3.1	3.3
3-11-67	1.21	1.04	240	230	15	23	2.94	309.6	-19	-2.5	3.1
Average	1.97	1.84	239	244	16.3	27.9	3.43	312.9	-16.4	2.3	4.2
Overall	Average		229	237	16.4	27.7	3.33	311.2	-17.8	2.6	3.8

As might be expected the moisture content is relatively quite high during these excessive snowfalls. The 700 mb mixing ratio ranges from 2.26 gm/kgm upward to 4.61 gm/kgm during these events averaging about 3.2 gm/kgm for unseeded and 3.4 gm/kgm for seeded cases, respectively.

Equivalent potential temperatures at 700 mb associated with these storms are also relatively high ranging from 299° K to 319° K for individual days. The average varies from 309.4° K for the unseeded events to 312.9° K for seeded cases.

Temperatures near cloud top (500 mb) range from -15° C to -23° C with an average of -19.1° C for the unseeded events. The seeded episodes have 500 mb temperatures ranging from -12° C to -21° C with an average of -16.4° C.

These excessive snowfall events generally occur with the 700-500 mb layer stable with respect to moist convection. Only the seeded case of April 10, 1965, shows a decrease of equivalent potential temperature through the layer.

Table XIX also shows that daily snowfalls of 1.20 inches water equivalent have occurred on Wolf Creek Pass during every month from November through April during the 1964-68 winter season. However, the month of December had 8 of the total of 15 occurrences and the six-week period from November 25 through January 8 accounts for almost three-fourths of all occurrences during the four-year period of study. The annual frequency of these events is about 4 per year.

The warmer cloud top temperatures (500 mb) during the seeded events are interesting. The difference of 2.7° C in the means of the unseeded and seeded cases results in a student's "t" value of 1.58 with 13 degrees of freedom. Thus, a null hypothesis that the means of the two samples are identical may be rejected at the 7% significance level. This indicates some possibility that more of these large daily storms are occurring at warmer cloud top temperatures during seeded years.

Two Day Snowfalls

Table XX shows the upper air climatology of two day storms on Wolf Creek Pass which produces 4.0 inches water equivalent at Wolf Creek West and/or Wolf Creek Summit. The annual frequency of such storms has been about one per year during the four years of study.

The strong orographic influence and unusually large moisture quantities characterize these storms. The wind flow is southwesterly with speeds generally 33 to 43 knots at 700 mb and 55 to 65 knots at 500 mb while these storms are in progress.

TABLE XX--Upper level meteorological parameters associated with excessive two day snowfalls on Wolf Creek Pass. Storm events have produced 4.0 inches water equivalent per 48 hours at Wolf Creek West and/or Wolf Creek Summit.

Date	W.C. West 2 Day Precip. (Inches)	W.C. Summit 2 Day Precip. (Inches)	700 mb Wind Direction (Degrees)	500 mb Wind Direction (Degrees)	700 mb Wind Speed (MPS)	500 mb Wind Speed (MPS)	700 mb Mixing Ratio (GM/KGM)	700 mb Equiv. Pot. Temp. (° K)	500 mb Temp. (° K)	Mean Temp. Advection (°C/12 hr)	Convective Instability (° C)
(Unseeded)											
12-19-67	1.97	1.65	220	240	18	28	2.43	304.8	-22	7.1	3.9
12-20-67	2.11	2.10	220	220	17	28	3.00	306.4	-21	0	3.5
Total	4.08	3.75									
	Average		220	230	17.5	28	2.72	305.6	-21.5	3.6	3.7
(Seeded)											
1-7-65	3.05	2.39	230	230	9	32	3.60	312.6	-13	0	10.4
1-8-65	1.52	.98	230	230	17	32	2.99	311.9	-18	0	1.5
Total	4.57	3.37									
12-6-66	2.43	3.03	260	280	22	29	4.42	317.1	-12	8.9	7.4
12-7-66	2.40	2.13	240	250	16	27	4.61	318.8	-14	3.1	3.3
Total	4.83	5.16									
	Average		240	248	16	30	3.90	315.1	-14.3		

The mixing ratio at 700 mb is generally near 3.0 gm/kgm or higher during these storms. The combination of the relatively warm and moist conditions results in 700 mb equivalent potential temperatures of 305° K to 319° K during these storms.

It is interesting that the unseeded two day storm contained cloud top temperatures (500 mb) that were several degrees colder than the two seeded storm events. The difference in the mean cloud top temperatures during the unseeded and seeded episodes is over 7 degrees. It is, of course, impossible to statistically test this result with the sample size available.

The four winter seasons of 1964-68 were surveyed for continuous storm periods resulting in a total of 3.5 inches water equivalent or more at Wolf Creek West and/or Wolf Creek Summit. Nine stormy periods met this criteria during the four years resulting in a frequency of a little more than two a winter season. Table XXI indicates the date and totals for these stormy episodes.

From Table XIX it is seen that over half of the stormy regimes have occurred during December in this particular four year study. However, with a sample taken over such a short time interval, it is probably unwise to place too much credence on the monthly distribution of these stormy episodes.

It does appear that prolonged snowstorms resulting in 3 to 8 feet of snow over a relatively few days can be expected about two times a year on the average at Wolf Creek Pass.

Table XXI also brings out another interesting point. During two-thirds of these stormy periods recording precipitation gages ceased to function correctly at one of the observing sites.

It is of interest that the heaviest storm period was not seeded. This pre-Christmas storm of 1967 was the result of the formation of a large, quasi-stationary upper level vortex centered generally over the area of Arizona and Southern California for several days., Because of its quasi-stationary nature abundant moisture was advected to the San Juan Barrier from off the Pacific coast of Southern California and Lower California. Favorable orographic flow persisted for several days resulting in 7.5 to 8.0 inches of water equivalent on the Pass.

E. Weather Modification Hydrology

1. Introduction

Most of the stable flow of streams in the Upper Colorado River Basin comes from snow melt. Flows during the snow melt period, normally April through August, account for 75 to 85% of total annual flow in Colorado River tributaries. If the flow that is delayed by passage through ground water is included, possibly 90% of the streamflow results from precipitation that fell as snow. Therefore, most of the effective precipitation for producing runoff falls in the winter and early spring months.

Average runoff per unit area varies from less than one inch annually in the lower elevation semi-desert area up to over twenty inches

TABLE XXI. --Continuous stormy periods at Wolf Creek Pass that resulted in total precipitation exceeding 3.5 inches water equivalent at Wolf Creek West and/or Wolf Creek Summit.

Winter Season	Period	Treatment	W.C. Summit Precip. (Inches)	W.C. West Precip. (Inches)
1964-65	Dec. 24-28	Seeded	4.02	M
	Jan. 5-8	Seeded	3.57	4.86
	April 2-15	Seeded	4.89	M
1965-66	Nov. 23-27	Not Seeded	M	3.89
	Dec. 22-25	Not Seeded	3.26	M
	Dec.30-Jan.2	Not Seeded	3.21	M
1966-67	Dec. 4-8	Seeded	6.21	5.36
1967-68	Dec. 13-21	Not Seeded	7.52	7.83
	Jan.27-Feb.1	Not Seeded	M	3.89

on the high elevation tributaries with the heaviest annual snow packs. Typically, flows are within 20% of average about one-half the time. Extreme flows range from 30 to 175% of average.

From a hydrologic standpoint, the best areas for attempts to increase runoff through weather modification are the areas of relatively heavy snow pack. In Colorado, these areas include the San Juan Mountain range, the headwaters of the Roaring Fork and Crystal Rivers, the headwaters area of the Upper Colorado including the Blue River and the Park Range tributaries to the Elk and Yampa Rivers. The Grand Mesa area of west central Colorado is a limited size but is also an area of relatively heavy snow pack.

Most of the surface water developed in the Upper Colorado River Basin in Colorado (including the San Juan and Green River Tributaries) flows out of the state. In the past 20 years it is estimated that an average of about 10 million acre-feet was produced in the Colorado River Basin in Colorado. Of this amount about 4% was delivered to other basins through trans-mountain diversions, and about 14% was consumptively used within the Basin.

The principal diversions to other basins include the Colorado-Big Thompson through Adams tunnel, the Twin Lakes Tunnel diversion from the Roaring Fork to the Arkansas, the Moffatt Tunnel diversion by the city of Denver from the Fraser to Boulder Creek, and the recently completed Blue River diversion by the city of Denver. The latter diversion had little effect on long term averages.

For the Green River in Wyoming, there are no diversions to other basins. It is roughly estimated that less than 10% of the water generated in Wyoming is comsumptively used in that state. In Utah, much of the water produced within the basin is taken out by trans-mountain diversions or is consumptively used. A rough estimate is that one-half of the flow generated within the Utah basins reaches the Green or Colorado Rivers. Flows of less than 100,000 acre feet a year are generated on the watershed of the Colorado River in New Mexico.

2. Snowpack-Runoff Characteristics

Snow water equivalent measured at mountain snow courses and winter precipitation measurements at high elevations have been the principal factors used in forecasting snow melt season flow in western streams for up to 60 years. The major effort in making streamflow forecasts started some 35 years ago. Forecasts are now made for all snow melt streams of the west. Extensive application of these forecasts has been made to various water management operations.

The characteristics of snowpack and streamflow relationship are important to various aspects of a program of weather modification for increasing water supplies. The quality of these relationships largely determines their usefulness for evaluating seeding effects, making conversions of measured precipitation changes to quantities of streamflow added, determining flood threats that might be accentuated from weather modification, etc.

A study has been made relating April 1 snow water equivalent on selected snow courses to April-August stream flow for 70 representative stations in the Upper Colorado River Basin. Streams in Colorado, Wyoming and Utah have been included. The selection of individual snow courses to be used was based on high correlation with runoff, a logical location in or near the watershed, and an adequate length of record (also runoff record). The longest record used was 20 years. The use of this length of record minimizes problems of the continuing changes in data gathering procedures and in water use practices. Snow course data is subject to gradual change because of changes in overhead interception and general exposure of terrain. There are at times drastic changes in the data sites caused by timber cutting, fire, widespread timber disease and construction activities. Snow courses affected by material change were not used in these comparisons except in perhaps two instances and these are not considered as extreme. Some snow courses have much better correlation with runoff than others. The reason is not always apparent but it generally is related to high elevations and a protected sampling area. Runoff records are affected by changing patterns of water use as well as improvements in water measuring techniques. Some of the stations in these comparisons are affected by trans-mountain diversions and water use above the station where measurements of diversions are either inadequate or missing. Most of these stations are near the Continental Divide in Colorado or on streams from the Uinta Mountains in Utah and Wyoming. For purposes of snow runoff relationships these diversions tend to be relatively constant and of lesser effect on larger streams. The lack of records on diversions account for low correlation on smaller streams to some degree.

Snow accumulation to April 1 (or maximum date) is the major factor affecting flow in snow melt streams. There are several other factors. These include precipitation after April 1 through the snow melt season, soil moisture conditions, and ground water levels on the watershed. The snow melt or temperature sequence also affects total runoff and especially peak stage. In most years these other effects tend to balance and approach an average over a season. They are difficult to evaluate unless there is an extreme and lengthy deviation of climatic conditions from normal. In the past 20 years, the 1957 water year was noted for excessive snow accumulation after April 1 and a delayed snow melt in Colorado mountains.

Flows of the previous year or more have a substantial effect on many watersheds. It is noted that flows for the years 1953, 1958, 1963 and 1965 tended to exceed that which should have been expected from the snow cover. These followed heavy runoff years. On the other hand flows in 1956 and 1962 were generally less than expected because these years followed two or three years of low runoff.

The period April - August, inclusive, is generally the best period to represent snow melt runoff in determining snowpack-streamflow relationships. At lower elevations the inclusion of March flows would be slightly preferable. Any period from March through September that includes May, June and July are highly correlated and represents a fair index of snow melt runoff in the Upper Colorado Basin. Direct snow melt runoff ranges from 75 to 85% of total annual runoff. If the flow that is delayed through groundwater storage is added, the snow melt runoff would probably account for near 90% of total annual flow.

Precipitation records during the winter and spring months at high elevation stations are also used to forecast streamflow. The practice is to adjust monthly total precipitation to give greater weight to mid-winter months. Where good precipitation records are available these records can be used as a satisfactory parameter to relate to subsequent runoff. No studies of these relations have been made at this time.

Runoff data, elevation of gaging stations and their drainage area were taken from appropriate tables in Surface Water Supply Papers published by the U. S. Geological Survey. Snow course data was obtained from data summary publications of the Soil Conservation Service. Detailed descriptions of stations and snow courses are shown in the respective reports and are consequently not included here. Table XXII presents a summary description of some of the more important geographic and hydrologic characteristics of selected streams within the Colorado River Basin and for downwind basins that would also be affected by weather modification within the Colorado River Basin.

The mean elevation of the watersheds was estimated roughly from 500-foot contour-scale 1:500,000 maps of states. The estimated elevation is believed to be correct within 300 feet.

The minimum snow line elevation is based on five inches of snow water equivalent on April 1 of an average year. The elevation of this line varies with aspect and exposure. Estimates were made from data on low elevation snow courses and personal observation of snow pack conditions for several seasons. An average of five inches water content is near the minimum snow pack that can produce runoff after satisfying soil moisture deficits, and transpiration and evaporation losses during the snow melt season.

The acre inches per acre is figured by dividing mean April-August runoff by the total area of the watershed. The runoff per unit area follows a pattern related to the size of the snow pack area of the watershed. This may not be related to total watershed area.

The estimate of acre-feet runoff per inch of snow water equivalent is based on the slope of the relationships points (estimated least square line). It is adjusted somewhat to reflect any deviation of the average of the elevations of the snow courses used from the average snow pack elevation of the watershed.

The percentage column represents the percent that one inch of snow water equivalent will produce of the total April-August runoff.

The correlation coefficient was calculated by the rank-difference (Spearman) method. This is a rough estimate. Correlation coefficients using the actual snow course and runoff data may vary up to .05 from that calculated by the rank-difference method. Typically the variation will be about .02. Data is available to calculate the least square line, the standard deviation of runoff, and a more accurate correlation coefficient.

In the Colorado River at Lee's Ferry, Arizona, one inch of snow water equivalent at the 10,000-foot level over the basin will produce about three quarter million acre feet during the snow melt season or one million acre feet annually. This excludes some two and one half to three million acre feet diverted or used in the Upper Basin.

Figures 51 through 56 show the relationship between April 1 snow cover and runoff for a few selected stations in the Colorado River Basin. These are considered representative of relationships that can be established for other areas.

A summary of the distribution of correlation coefficients obtained for the 70 streams studied is shown in Figure 57. It can be noted that 8, or 11%, of the streams have correlations with snowpack of .9 or better and 50, or 71%, are correlated at .8 or better.

TABLE XXII. --Summary of data.

Name of Watershed	Elevation of Station	Drainage Area Sq. Miles	A Average Flow 1000/ A.F.	B Mean Elevation Ft.	C Elevation Min. S.P.	D Flow Ac. Inch Per Ac.	E Ac.Ft. Flow Per Inch SWE.	F Percent Flow Per Inch SWE.	G Approximate Corr. Coefficient	Snow Course Elevation
Colorado River										
Eagle at Red Cliff	8,800	73	24	10,100	9,100	6.1	2,000	8.2	.81	10,600
Home Stake near Red Cliff	8,800	59	51	10,800	9,100	16.2	5,000	9.8	.93	10,000
Roaring Fork at Aspen	7,800	109	93	10,600	8,800	16.0	6,700	7.2	.81	9,700
Crystal above Avalanche Cr.	6,900	167	180	9,600	8,500	16.6	12,000	6,7	.87	9,300
Blue near Dillon	8,670	120	40	10,400	8,600	6.4	4,400	9.1	.86	10,000
Blue above Green Mt. Reservoir	7,700	599	231	9,900	8,600	7.3	20,000	8.8	.93	10,700
Snake at Montezuma	9,300	59	33	10,800	8,600	10.2	2,900	8.8	.86	10,500
Ten Mile near Frisco	9,090	94	53	10,500	8,600	10.5	4,400	6.5	.95	10,300
Williams near Leal	8,700	86	56	9,700	8,400	9.8	5,500	9.9	.83	9,500
Frazer near Winter Park	8,900	27	21	10,800	8,600	14.8	1,400	6.6	.88	9,700
Colorado below Baker Gulch	9,300	53	51	10,700	8,400	17.9	4,000	7.6	.75	9,700
Arapaho at Monarch Lake Outlet	8,500	47	54	10,700	8,300	18.8	4,200	7.8	.87	8,900
Willow below Willow Creek Reservoir	8,109	134	45	9,300	8.100	6.3	4,800	10.7	.77	9.200
Piney near State Bridge	7,270	83	46	8,900	8,900	10.3	3,400	7.4	.91	8,900
Uncompahgre at Ridgeway	6,890	150	83	10,000	8,900	10.3	4,500	5.5	.83	10,500
Animas at Howardville	9,620	56	64	10,900	8,100	22.0	3,500	5.5	.85	10,900
South Platte										
North Platte at Northgate	7,810	1,431	225	9,200	8,700	3.0	20,000	8.9	.88	9,300
Poudre near Rustic	7,610	199	138	9,800	8,900	13.1	12,000	6.1	.85	10,200
Big Thompson at Estes Park	7,500	138	78	9,900	8,800	10.6	4,500	5.8	.76	10,000
St. Vrain at Lyons	5,300	212	68	9,900	8,800	6.1	6,000	8.8	.61	10,000
Clear Creek at Golden	5,730	399	130	8,900	9,000	6.1	10,000	7.7	.72	9,800
Rio Grande										
Goose Creek at Wagon Wheel Gap	8,640	90	39	10,300	9,000	8.1	2,300	5.9	.84	10,000
Rio Grande at 30-Mile Bridge	9,300	163	136	10,820	9,000	15.6	8,000	6.0	.90	10,200
S.F. Rio Grande at South Fork	8,220	216	120	10,800	8,800	10.2	7,000	5.8	.92	10,000
Alamosa Above Terrace Res.	8,600	107	70	10,600	8,900	12.3	4,000	5.7	.90	10,000

A. Average April-August runoff in 1,000 acre feet.
B. Mean elevation of watershed.
C. Average minimum elevation of winter snow pack (5 inches or more average for April)
D. Average runoff in acre inches per acre.
E. Average runoff in acre feet per inch of snow W.E.
F. Percent of average runoff for an inch of snow W.E.
G. Approximate correlation coefficient between snow W.E. index and April-August runoff.
H. Elevation of snow course or average elevation of snow courses used.

TABLE XXII - Continued:

Name of Watershed	Elevation of Station	Drainage Area Sq. Miles	A Average Flow 1000/ A.F.	B Mean Elevation Ft.	C Eleva- Min. S.P.	D Flow Ac. Inch Per Ac.	E Ac.Ft. Flow Per Inch SWE.	F Percent Flow Per Inch SWE.	G Approximate Corr. Coefficient	Snow Course Elevation
Rio Grande continued:										
Conejos near Mogote	8,270	282	215	10,200	9,000	14.1	10,000	4.6	.89	10,000
Colorado River										
Navaho near Chromo	7,940	70	50	9,800	8,900	10.8	4,000	8.0	.84	10,000
Los Pinos below Vallecito	7,515	284	145	9,800	8,700	9.9	13,000	9.0	.88	10,500
Hermosa near Hermosa	6,705	172	60	9,600	8,600	6.6	6,000	10.0	.89	9,700
Dallas near Ridgeway	6,930	90	14	8,500	8,700	2.9	2,000	14.2	.79	9,800
Colorado near Colo-Utah Line	4,370	17,900	2,900	6,500	8,800	3.0	350,000	12.1	.90	9,900
Buzzard near Collbran	6,955	139	18	9,000	8,700	3.4	3,500	18.5	.72	9,500
Roaring Fork near Glenwood	5,720	1,460	600	9,000	8,600	7.7	60,000	10.0	.93	10,000
Frying Pan near Norrie	8,410	90	70	10,700	8,500	14.5	5,000	7.2	.92	9,700
Colorado below Dotsero	6,130	4,390	1,250	6,500	8,700	5.3	140,000	11.2	.90	10,000
Eagle near Gypsum	6,270	957	340	9,400	8,900	6.8	30,000	8.8	.92	10,000
Rock Creek near Taponas	8,544	48	18	9,100	8,800	7.0	2,200	14.6	.80	9,100
Dolores below Rico	8,422	105	75	9,800	8,500	11.2	17,000	9.4	.87	10,700
San Juan at Pagosa Springs	7,052	298	175	9,600	8,900	11.0	9,000	5.2	.92	10,000
San Miguel at Placerville	7,055	308	125	9,100	8,500	7.6	10,000	8.0	.83	10,200
San Juan at Rosa, N.M.	5,980	1,990	600	7,500	8,300	5.7	35,000	5.9	.90	10,000
East at Almont	8,007	295	230	9,500	8,200	14.7	14,000	6.1	.85	9,000
Tomichi at Gunnison	7,673	1,020	130	9,200	8,200	2.4	17,000	12.9	.87	10,700
Gunnison near Gunnison	7,670	1,010	425	9,300	8,200	7.9	45,000	10.7	.87	9,800
L. Fork Gunnison at Gateway	7,827	338	145	9,500	8,300	8.1	8,500	5.6	.84	10,900
N. Fork Gunnison at Somerset	6,038	521	260	8,500	8,100	9.4	18,000	7.0	.86	9,500
S. Fork White near Buford	6,970	170	140	8,900	7,900	15.5	7,000	5.0	.82	9,000
White near Buford	7,010	254	140	8,700	7,700	10.3	12,000	8.5	.85	8,500
Yampa near Oak Creek	7,100	227	55	8,300	7,500	4.5	8,000	7.3	.85	8,500
Elk at Clark	7,270	206	210	8,700	7,200	18.9	7,000	3.4	.85	8,700
Williams Fork near Pagoda	6,830	150	75	8,400	7,300	9.3	7,000	9.3	.86	8,800
Little Snake near Slater	6,831	285	150	8,400	7,200	9.8	7,000	4.6	.90	9,800
Green at Warren Ridge	7,470	468	325	8,500	7,500	13.0	14,000	4.2	.90	8,200
Green at Green River, Wyoming	6,050	10,000	950	7,300	7,500	1.8	50,000	5.3	.90	8,200
Pine above Fremont Lake	7,540	76	115	8,800	7,400	28.2	8,000	7.0	.90	8,800
New Fork near Boulder	6,900	552	240	8,300	7,400	8.2	10,000	4.2	.89	8,300
Boulder below Boulder Lake	7,200	130	135	8,700	7,400	19.3	10,000	7.4	.82	8,750
Big Sandy near Farson	6,800	320	50	8,100	7,600	3.0	4,000	8.0	.81	9,000

TABLE XXII - Continued

Name of Watershed	Elevation of Station	Drainage Area Sq. Miles	A Average Flow 1000/ A.F.	B Mean Elevation Ft.	C Elevation Min. S.P.	D Flow Ac. Inch Per Ac.	E Ac.Ft. Flow Per Inch SWE.	F Percent Flow Per Inch SWE.	G Approximate Corr. Coefficient	Snow Course Elevation
Colorado River continued:										
Blacks Fork near Milburn	8,380	156	100	9,000	8,400	12.0	4,500	4.5	.65	9,800
Henry's Fork near Linwood, Utah	6,120	520	45	7,000	8,400	1.6	7,200	15.2	.48	8,730
Ashley near Vernal, Utah	6,250	101	55	8,600	8,300	10.2	4,000	7.3	.74	9,500
Whiterocks near Whiterocks	6,980	115	65	9,000	8,500	10.6	4,000	6.2	.70	10,300
Unita near Leola	6,910	181	100	9,000	8,500	10.3	4,000	4.0	.70	10,300
Yellowstone near Altonah	7,400	131	75	9,200	8,300	10.7	4,000	5.4	.78	10,300
Rock Creek near Mt. Home	7,250	149	110	9,400	8,200	13.7	6,000	5.5	.78	10,300
Duchense near Tabiona	6,227	352	100	8,800	8,000	5.2	6,500	6.5	.90	7,800
Price near Hiener	6,000	455	70	7,800	7,500	2.9	5,000	14.0	.90	8,700
Huntington near Huntington	6,200	188	60	8,200	7,500	6.0	3,500	10.0	.89	9.800
San Rafael near Castlerock	5,390	927	100	7,200	7,700	2.0	9,000	9.0	.88	9.800
Colorado at Lee's Ferry, Arizona	3,106	108,000	9,000	-----	-----					8,500 to
4/1 Snow Data						1.7	800,000	7.3	.89	10,700
4/1 Snow Data plus watershed condition index									.93	
5/1 Snow Data									.95	
5/1 Snow Data plus watershed condition index									.96	

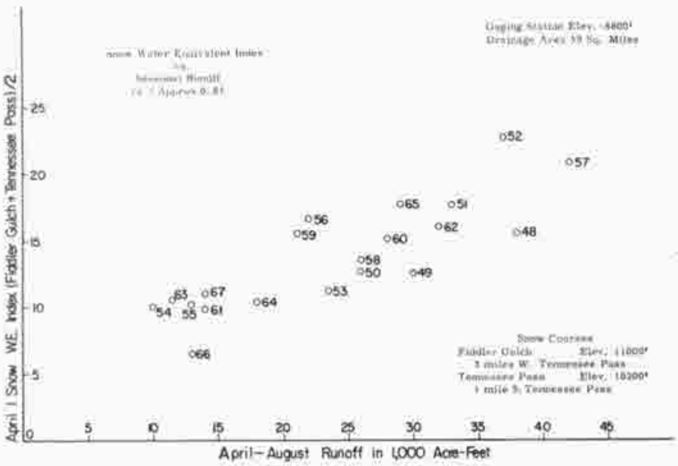


Figure 51. --Eagle at Redcliff (not corrected for diversions).

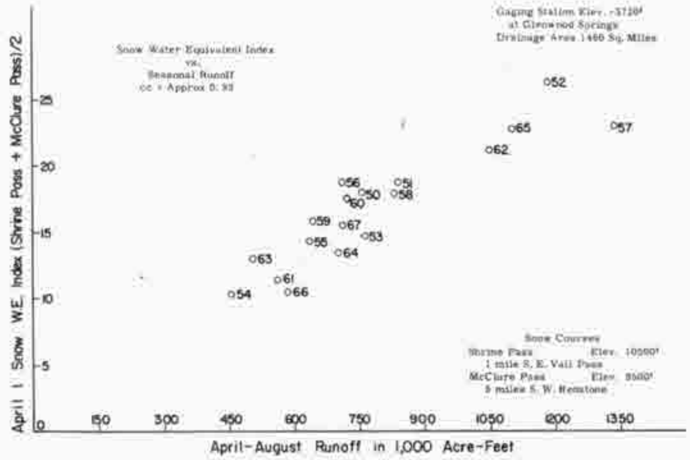


Figure 54. --Roaring Fork at Glenwood Springs.

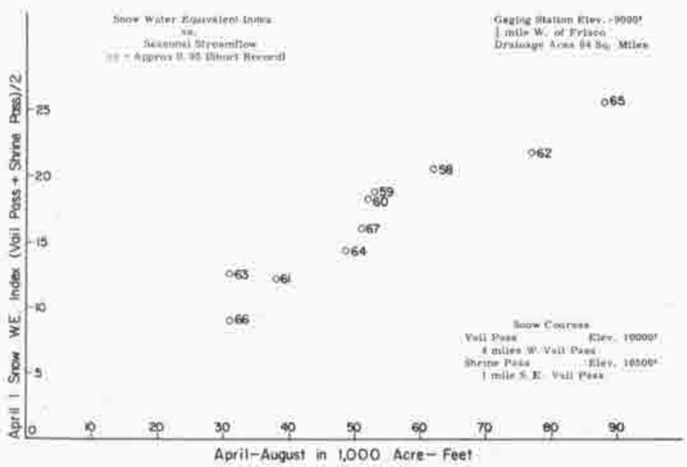


Figure 52. --Ten Mile near Frisco

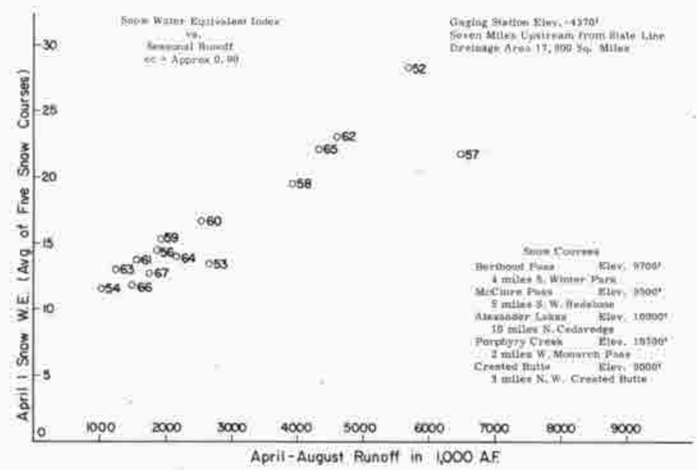


Figure 55. --Colorado River near Colorado-Utah Line.

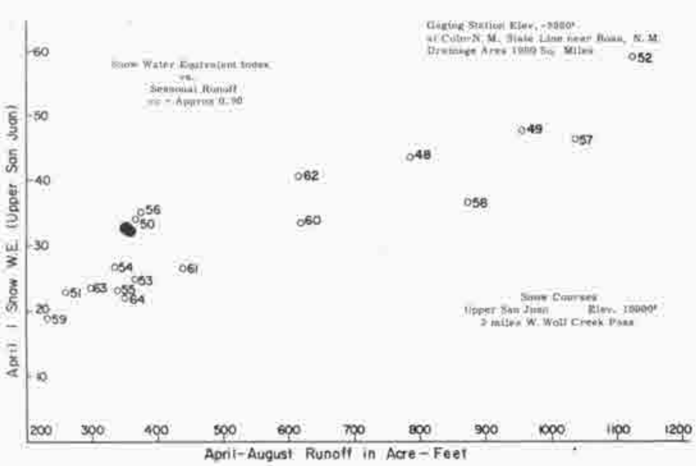


Figure 53. --San Juan at Rosa, New Mexico.

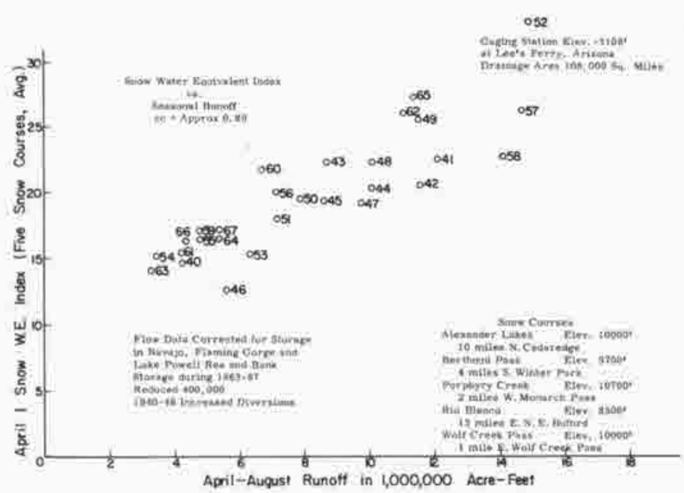


Figure 56. --Colorado at Lee's Ferry.

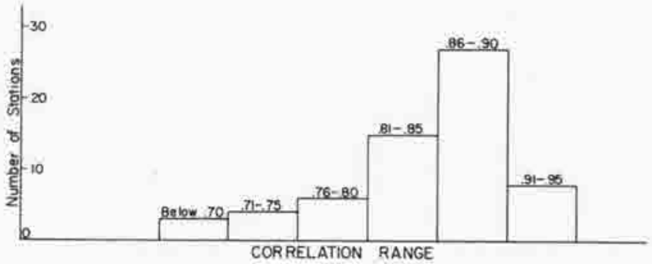


Figure 57. --Snow water equivalent index vs. seasonal runoff, Colorado River Basin. No. of stations with indicated correlation coefficients in total of 70 stations.

3. Trends in Streamflow and Streamflow Records During the Past Sixty Years

A limited study of snow course and streamflow records show that averages have remained rather stable over the past 25 to 35 years. However, the years of low runoff tend to occur consecutively. It is not unusual to have a five-year or longer average which is 10%, or sometimes even 20%, more or less than a 30-year average. Further, for the few runoff records which are available, the average for the period from about 1906 or 1910 to 1925 is 120 to 140% greater than for the past 20, 30 or 40 years.

Figure 58 shows the consecutive five-year averages for the period 1906-1967 for the Roaring Fork at Glenwood Springs and the five-year averages for the period 1911-1967 for the Fraser near Winter Park. Both stations have been corrected for measured trans-mountain diversions. The drop in flow since the 1910-1920 period of the Roaring Fork is most dramatic. Present use of water within this Basin represents only some 5% of the total water produced. This amount has probably increased slightly since the 1910-1920 period, but is not significant.

Figures 59 and 60 show accumulated runoff for the Roaring Fork at Glenwood Springs and the Fraser near Winter Park in their respective records. Both stations show a definite break in trends of runoff in the middle 1920's, but are reasonably consistent for periods before and after that date. It is believed that further investigations would show similar trends for streams in the southwest with sufficient records. At the moment, no explanation is available to explain the change. It also appears there is a slight trend toward a decline in streamflow during the past 35 years, but it is not substantial.

Some years ago an interagency group made an analysis of a large number of streamflow, precipitation and snow course records. The studies were based on the question "At what period of record will the following year be closest to the average for the period?" On the average this period turned out to be 17 years with about half of the total being between 15 and 20 years. The maximum record considered was 30 years, a common base for USGS and USWB at that time.

Both the lack of records and the desirability of having data represent present conditions indicates that data based on the most recent periods is preferable for determining means or deviations that are most likely to occur during the periods immediately ahead.

4. The Use of Snow Course Data for Evaluation of Weather Modification

Snow courses are utilized to provide an index of snow water accumulation in an area. They have only limited application for verification of weather modification activities. The measurement procedure itself is rather gross, but perhaps more accurate than other methods except daily measurements of snowboards. There is some variation in melting among the years up to April 1, especially at exposed locations under 10,000 feet. Variation in melting after April 1 is so extreme as to preclude use of snow courses to check weather modification results after than date.

The use of snow course data is limited further for cloud seeding done on a random basis. This becomes particularly serious when the high probability that both increases and decreases in precipitation have resulted during experimental-type seeding. Snow courses will tend to show even minor changes in patterns between areas over the years.

Several combinations of April 1 snow water at upwind snow courses in comparison with those at Wolf Creek Pass have been investigated. These courses are located in the western end of the San Juan Range on the headwaters of the Dolores, Animas and Rio Grande. Correlation coefficients between snow courses in the upwind area and those at Wolf Creek Pass varied from 0.85 to 0.93.

An exploratory-type investigation of snow course data has been carried out for seeded years at Climax and at Wolf Creek. For this exploration-type investigation at Climax, the period 1960-69 was considered to have been seeded. Actually only about one-third of the precipitation days were seeded and an analysis of precipitation data, presented in V.B above, indicate that both increases and decreases have occurred. The 1939-59 period was used for non-seeded years, although some commercial seeding was carried out in this area on some of those years. There tended to be more snow accumulated in Fremont Pass area in the 1960-69 period than during the years before 1960 on April 1 relative to surrounding snow courses. The Fremont Pass area tended to have slightly less snowfall relative to other areas up to March 1. The snow accumulation during March was high in comparison to surrounding areas so that the overall accumulation to April 1 was somewhat greater than would be expected. If true, this result might be expected from the model presented in V.A above if there were more cases with cold 500 mb temperatures before March (these would cause decreases) and more cases with 500 mb temperatures greater than -20 during

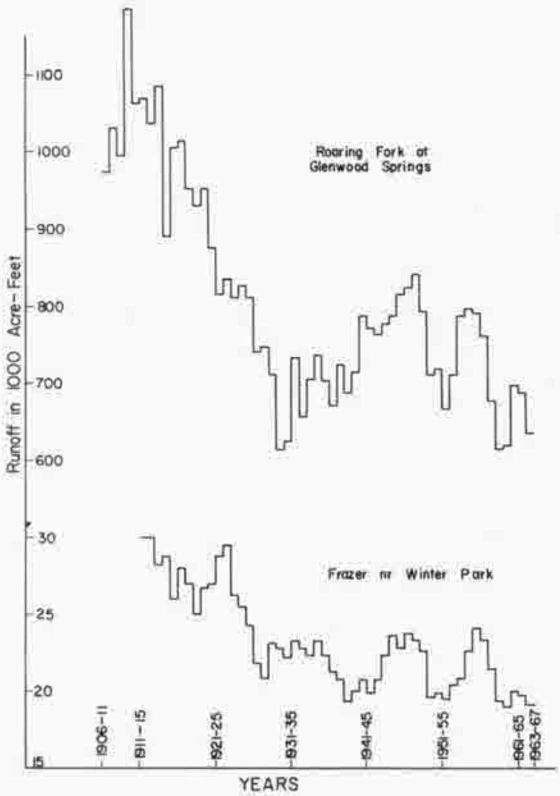


Figure 58 . --Streamflow--5-year moving average. Annual total corrected for diversions.

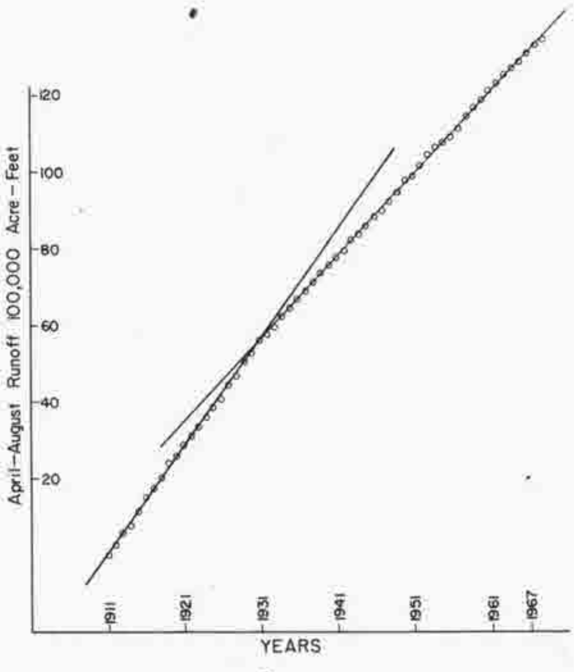


Figure 59. --Accumulated flow 1906-67, Roaring Fork at Glenwood Springs.

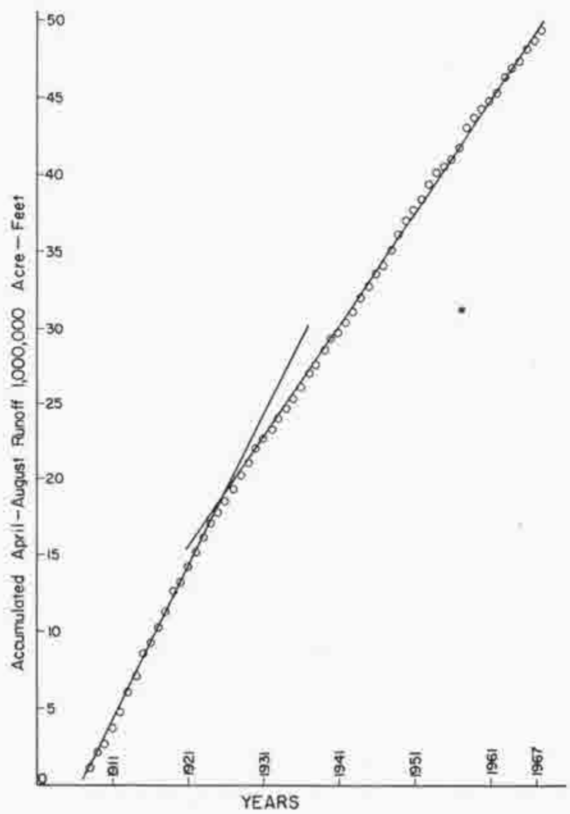


Figure 60. --Accumulated flow 1911-67, Fraser near Winter Park (corrected for diversions).

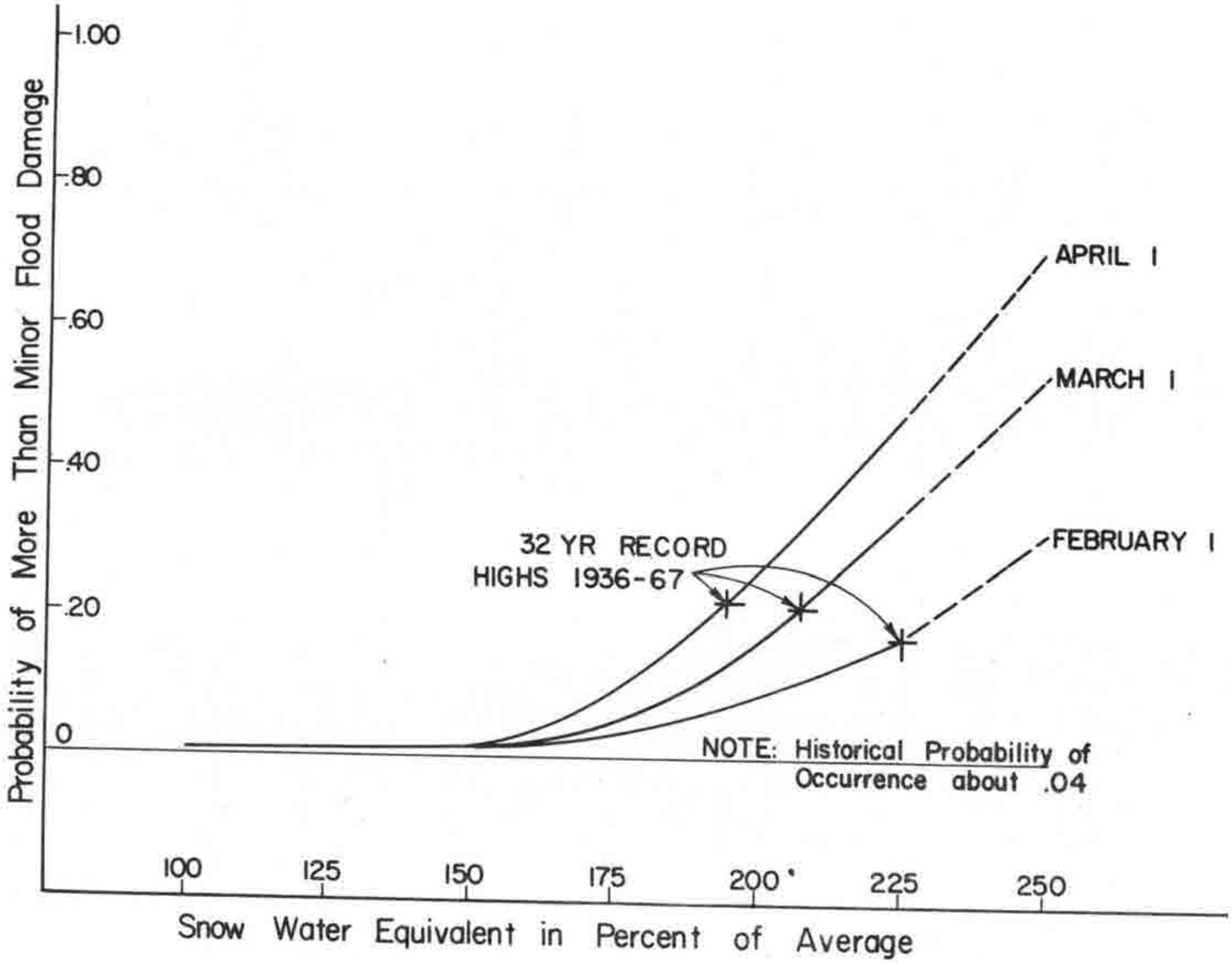


Figure 61. --Typical probability of more than minor flood damage for tributary streams to the San Juan during snow melt.

March (these would produce increases).

At Wolf Creek there was an average of 17% greater snow accumulation during the seeded 1965, 1967, and 1969 seasons than during the previous eight year period, including the randomized non-seeded years of 1966 and 1968 in relation to the snow at upwind control stations. Again, it must be remembered that the seeding was carried out under meteorological stratifications that could be expected to have produced both increases and decreases in precipitation.

These studies of the use of snow course reading for evaluation of weather modification are just getting underway and are being continued. It is not expected that snow course data will prove very useful for weather modification evaluation for reasons presented above.

5. Investigation of Flood Potential Resulting from Snowmelt

a. General discussion

On Colorado River Tributaries most of the annual peak streamflow comes during the highest snow melt runoff, usually in May or June. In rare years annual peaks may occur in late April on a few tributaries or in early July in a heavy snow year when weather factors combine to delay snow melt. Snow melt peaks rarely are responsible for material flood damage. These annual peaks seldom vary more than about 5 ft in actual stage and overflows that do occur are over meadow or unoccupied land near the rivers.

Snowmelt peak flow is moderately well related to total snow melt season flow. In the few instances where relationships between snow melt peak flow and total snow melt season flow have been compared, the correlation coefficient ranged between 0.50 and 0.80. Temperature sequences have a substantial effect on rate of snow melt runoff, as well as total snow pack. The area of snow covered ground is the other major factor in affecting snow melt rates. The area of snow covered ground at any specific date during the snow season tends to be well related to the relative depth of the snow pack of the preceding season. The highest recorded peak flows for San Juan and Rio Grande tributaries in southwestern Colorado and adjacent streams occurred on October 5, 1911, a date well after the end of the snowmelt period. These peaks were two to three times the volume of typical snow melt peaks and obviously was the result of heavy rains. There are several other records on streams rising in the San Juans where annual peak flows occurred in late July or during August, also well past the snow melt peak. These other records of peak flow were in the general range of maximum snow melt peak flows at the gaging stations. It is suspected that flows were much higher on smaller tributaries draining the watersheds where the isolated storms occurred. Peaks outside of the snowmelt season occur about once in ten years in the San Juan Mountains area and less frequently on other Upper Colorado River watersheds. These periods of intense flow produce extreme peaks but do not produce substantial portions of the annual flow since they are of short duration.

b. Flooding in Ouray, Colorado, Area

There is a history of flooding in the Ouray, Colorado, area but there is limited record of high flows at regular gaging stations.

There was a gaging station in operation at Ouray, including the Uncompahgre and Canyon Creek, for the period 1914-29. The station at Ridgeway was established in 1957. This station is about 10 miles downstream from Ouray. They are probably comparable as to total flow but have very little relation as to peak flow.

The highest flow recorded at the Ouray Station was on June 11, 1931 at 2400 cfs at a gage height of 6.1 ft. The highest gage height recorded was 13.3 ft on July 27, 1927, because of a log jam. There have no doubt been other unrecorded log or ice jams in the area. A few other streams in the area have records of above bankful stages in winter months. The 1927 water year was one of high runoff, probably exceeded four or five times in the past 50 years, and then by less than 15%. The maximum flow which has occurred since the turn of the century was probably on October 5, 1911, the above mentioned period of high rainfall in the area.

The records of major floods in Ouray are based on limited flood surveys and newspaper accounts. The most recent severe flood occurred on July 11, 1965. The flood was caused by rainfall on small drainages of one to three square miles near town on steep slopes (Portland and Cascade Creeks). The rainfall occurred between 6:00 p.m. and 11:00 p.m. The peak occurred about midnight. The flow through Ouray was estimated to be in excess of 8000 cfs. There is no indication of how the estimate was made or the authority for making the estimate. The flood damage was caused by mud and rock slides blocking the creeks at the highway bridge and the clogging of a flume (apparently a by-pass) in the downtown area. Damage was estimated at $200,000.

The precipitation record at Ouray shows only.04 inch on July 11; 0.46 on July 12; and 0.51 on July 13. The newspaper account credits the flood to a cloudburst on the slopes above town. The account also mentions rain hampering cleanup on July 12 and 13. The gaging station on the Uncompahgre at Ridgeway, 10 miles downstream, recorded a daily peak of 660 cfs on July 11, rising to 1020 cfs on July 12 and receding to 880 cfs and 631 cfs on July 13 and 14, respectively. If the peak flow did reach 8000 cfs which must be questioned, it would have been of very short duration.

The only remote contribution from snow melt to this flood was that the peak flow was relatively late in 1965. It occurred on June 20 at 1200 cfs at Ridgeway. The year 1965 was a moderately heavy snow year, exceeded about 3 years in 25. Watershed soils were still saturated, a near normal situation. With the apparent rain intensity soil moisture conditions were a minor factor.

A similar storm occurred on July 25, 1929 (possibly a more severe storm), and storms of lesser magnitude were reported by the newspaper on August 22, 1909, July 27, 1927, and August 2,

1951. The recording stations show only the July 27, 1927, storm and that as nothing particularly severe.

In summary, floods at Ouray have resulted from intense summer season rainfalls. No information has been uncovered that indicated snow melt presents a serious flooding problem in the Ouray area.

c. Snowmelt Peak Flow Estimates for the San Juan Area

Snow melt peaks rarely cause material flood damage in the San Juan Mountain area. The greatest peak flows have occurred outside of the snow melt season and have ranged from near the maximum snow melt peak to three or four times this amount. Local flood damage is much more likely to be caused by temporary debris jams than by lack of normal channel capacity.

However, the probability of high peak flows does increase with the snowpack. There is the probability that some combination of snow melt and rainfall will combine to produce flood problems from once in twenty to once in fifty years.

The maximum flow recorded during the period 1936-67 for six major streams originating in the San Juan Range ranged from 188% of average for the Conejos near Mogote to 240% of average for the South Fork of the Rio Grande at South Fork, Colorado. Since the Conejos and main stream Rio Grande have substantial reservoir control the more practical limits are 200 to 240% of average. There were no excessive summer rainfalls covering a large area in the 1936-67 period although in 1941 and 1949 and to a lesser extent in 1957 summer rainfall (during the snowmelt season) was well above average. The maximum snow melt peak on these streams occurred in June, 1927, before snow pack records were available. The range was from about 300 to 500% of the average snow melt peak. The maximum snow pack in this area occurred in 1952. All peak flows were less than should have been expected. The flows in this year should have been exceeded in 60 to 75% of the years. In 1952 there was some channel cleaning in the Dolores and some diking near the town of Dolores. The reservoirs on the Rio Grande were at low levels, due to three previous years of low flow. Complete filling was delayed. It is estimated that peak flow on the Rio Grande was probably reduced from 10,000 to 11,000 cfs to about 7,000. There was no material flood damage.

Table XXIII shows the chances that specified percent of average peak flows will occur based in the 1936-67 records. Flows are going to exceed 200% of average about once in 15 years and 250% of average about once in 25 years.

TABLE XXIII.--Probability of exceeding specified peak flows during snowmelt for the period 1936-67.

Stream	Percent of Average Flow 50	75	100	125	150	175	200	225	250
S. Fork Rio Grande at South Fork	.98	.86	.50	.32	.20	.13	.09	.07	.05
San Juan at Pagosa Springs	.98	.80	.50	.38	.24	.14	.08	.06	.04
Animas at Durango	.98	.80	.48	.28	.17	.10	.06	.04	.03
Dolores at Dolores	.98	.79	.49	.30	.19	.11	.07	.04	.03

Note: Rio Grande near Del Norte and Conejos at Mogote not included because of substantial regulation of flow.

Extension of the probability curves indicate that 300% of average will be exceeded about once in 50 to 75 years.

Streams like the Conejos which flows across a flat area in San Luis Valley where any peak flow near or above average could cause flooding of lowlands. This is one of the factors in operations of Platoro Reservoir--to reduce peak flow to about 2000 cfs or 80% of average.

The correlation coefficient between April 1 snow water equivalent and peak flow are only in the range 0.3 to 0.7. The higher correlations exist on the high elevation gaging stations such as the San Juan at Pagosa Springs and the South Fork of the Rio Grande at South Fork. Correlation coefficients decline with the distance from the snow pack area. Typical scatter diagrams for snow water equivalent versus peak flow for the Animas at Durango and the Dolores River at Dolores are shown in Figures 60 and 61.

A study was made of the probability of occurrence of certain flows from a specified snow pack on February 1 and April 1. The results are listed in Tables XXIV through XXIX. The period used was 1936 through 1967. Snow data had to be estimated for up to 5 years on February 1 for some streams. The following is the list of streams:

South Fork Rio Grande at South Fork
Animas at Durango
San Juan at Pagosa Springs
Dolores at Dolores
Rio Grande near Del Norte
Conejos near Mogote

The least square line was calculated using all data. The standard deviation was calculated using only those years where either the snow water equivalent or peak flow was above average. This included 60 to 70% of the total (32 years). In low flow years the numerical variation is small as compared to high flow years. It is believed that a standard deviation based on high flow years, which is slightly higher (20 to 30%) is more realistic. The probability envelopes were considered as straight lines rather than curves with more deviation near the extremes of data.

There is substantial variation in probability of peak flow among the six streams.

The Rio Grande and Conejos show little tendency toward high flows but this is caused by reservoir regulation especially since about 1950. It was not considered practical to make full corrections for this control.

These tables show that a 200 to 250% peak in streamflow is not very probable in years with a normal snow pack. If April 1 snowpack is in the range of 200% of normal, the chances of minor flood damage become significant. Minor flooding is defined as bankful plus flood of unoccupied bottomland in some locations.

The probability of 200 to 250% of average peak flow from a 200% of average February 1 snow pack is roughly one-fourth to one-third of that for April 1.

Figure 61 shows the general probability of specified snow water equivalents causing more than minor flood damage. The probability of more than minor flood is very low if snow pack additions from weather modification are avoided when snow pack is in excess of 175% of average on February 1, 160% of average on March 1, and 150% of average on April 1. Probabilities do not become large, particularly for February and March observations, with snow pack of 200%. With the occurrence of a very rare accumulation of snow pack of 225% to 250%, seeding efforts for only very cold cases might be considered to reduce precipitation.

Figures 62 and 63 are scatter diagrams for snow water equivalent versus peak flow for the Animas at Durango and the Dolores at Dolores.

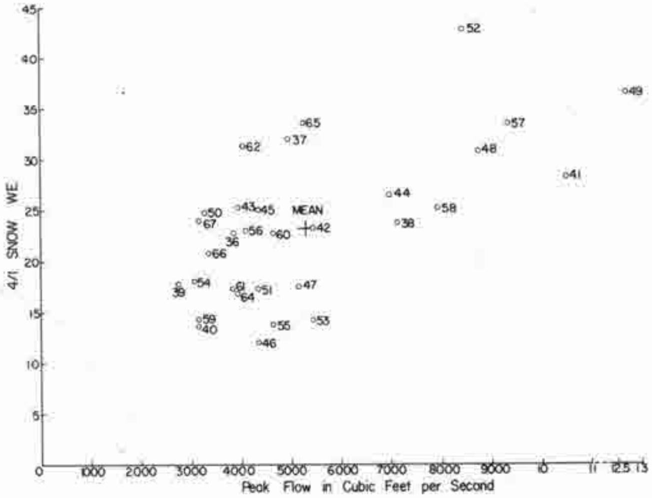


Figure 62. --Animas at Durango. Average Lizard Head and Wolf Creek Pass versus snow melt peak flow.

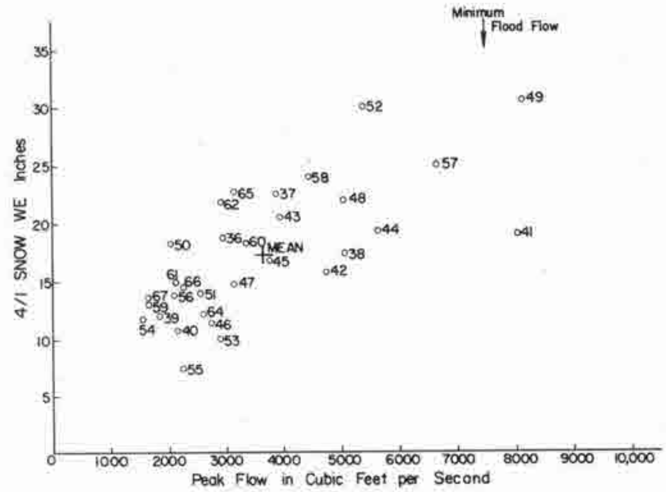


Figure 63. --Dolores at Dolores. Lizard Head snow course versus peak flow.

TABLE XXIV. --Probability of exceeding a specific flow in percent of average if snow water equivalent is a specific percent of average --South Fork--Rio Grande at South Fork, 1936-67.

Feb. 1 Snow W. E. % Avg.	Peak Runoff in Percent Avg. 100	125	150	175	200	225	250
100	.52	.37	.25	.12	.07	.03	.01
125	.68	.50	.35	.22	.12	.04	.02
150	.82	.67	.50	.32	.18	.10	.03
175	.95	.77	.68	.50	.34	.20	.06
200	.98	.96	.90	.65	.45	.26	.23
225	.99	.98	.96	.92	.62	.40	.38

Maximum snow WE 238% Maximum Peak Flow 240%

Apr. 1 Snow W. E. % Avg.	100	125	150	175	200	225	250
100	.35	.11	.04	.01	.01		
125	.78	.54	.26	.10	.02	.01	.01
150	.98	.92	.74	.50	.25	.07	.01
175	.99	.99	.97	.90	.75	.50	.11
200	.99	.99	.99	.99	.95	.80	.50

Maximum snow WE 187% Avg. Max. Peak Flow 240%

Based on Wolf Creek Pass Snow Course

TABLE XXV. --Probability of exceeding a specific flow in percent of average if snow water equivalent is a specific percent of average--Animas at Durango, 1936-67.

Feb. 1 Snow W. E. % Avg.	Peak Runoff in Percent Avg. 100	125	150	175	200	225
100	.52	.32	.16	.07	.02	.01
125	.68	.44	.25	.12	.03	.01
150	.79	.55	.40	.20	.08	.02
175	.90	.77	.54	.34	.15	.05
200	.96	.90	.73	.50	.28	.11

Max. Snow W. E. 183% Avg. Max. Runoff 216% Avg.

Apr. 1 Snow W. E. % Avg.	100	125	150	175	200	225
100	.55	.30	.14	.06	.01	.01
125	.75	.52	.27	.12	.04	.01
150	.85	.70	.47	.25	.10	.02
175	.95	.83	.67	.41	.18	.06
200	.99	.94	.80	.58	.36	.17

Max. Snow W. E. 184% Avg. --Max. Runoff 216% Avg.

Based on Lizard Head and Upper San Juan Snow Courses

XXVI. --Probability of exceeding a specified flow in percent of average if snow water equivalent is a specific percent of average--San Juan at Pagosa Springs, 1936-67.

Feb. 1 Snow W. E. % Avg.	Peak Runoff in Percent Avg. 100	125	150	175	200	225
100	.55	.32	.09	.02	.01	
125	.65	.47	.25	.11	.03	.01
150	.74	.65	.34	.14	.07	.02
175	.81	.58	.47	.21	.11	.03
200	.87	.73	.32	.27	.12	.04
225	.92	.80	.65	.38	.15	.06
250	.96	.90	.75	.52	.23	.09

Maximum Snow Pack 230% Avg. Max. Peak Flow 210% Avg.

Apr. 1 Snow W. E. % Avg.	100	125	150	175	200	225
100	.50	.24	.09	.01		
125	.80	.52	.25	.10	.02	.01
150	.97	.89	.70	.30	.12	.02
175	.99	.98	.86	.70	.48	.15
200	.99	.99	.96	.85	.75	.40

Maximum Snow WE 180% Avg. Max. Peak Flow 210% Avg.

Based on Upper San Juan Snow Course

TABLE XXVII. --Probability of exceeding a specified flow in percent of average if snow water equivalent is a specific percent of average--Dolores at Dolores, 1936-67.

Feb. 1 Snow W. E. % Avg.	Peak Runoff in Percent Avg. 100	125	150	175	200	225	250
100	.55	.44	.30	.12	.07	.02	.01
125	.68	.48	.32	.18	.09	.03	.01
150	.76	.56	.42	.25	.13	.04	.02
175	.83	.65	.50	.33	.16	.07	.02
200	.87	.70	.56	.47	.20	.10	.03
225	.90	.80	.61	.50	.28	.13	.07
250	.93	.88	.74	.57	.35	.18	.10

Max. Snow W. E. 258% Max. Peak Flow 225%

Apr. 1 Snow W. E. % Avg.	100	125	150	175	200	225
100	.55	.40	.20	.10	.02	.01
125	.78	.55	.36	.20	.07	.02
150	.88	.78	.52	.35	.20	.08
175	.97	.91	.79	.51	.37	.10
200	.99	.95	.90	.79	.50	.32
225	.99	.98	.94	.90	.77	.49

Max. Snow W. E. 175% Max. Peak Flow 225%

Based on Lizard Head Snow Course

XXVIII. --Probability of exceeding a specific flow in percent of average if snow water equivalent is a specific percent of average. Rio Grande near Del Norte, 1936-67.

Feb. 1 Snow W. E. % Avg.	Peak Runoff in Percent Avg. 100	125	150	175	200	225	250
100	.55	.40	.21	.08	.02	.01	
125	.64	.45	.24	.10	.03	.01	
150	.70	.48	.27	.12	.03	.01	.01
175	.75	.50	.29	.13	.04	.01	.01
200	.79	.53	.31	.14	.06	.02	.01
225	.83	.57	.35	.16	.08	.02	.01
250	.86	.65	.42	.21	.10	.02	.01

Maximum Snow W.E. 236% Max. Peak Flow 200%

Apr. 1 Snow W. E. % Avg.	100	125	150	175	200	225
100	.55	.35	.12	.04	.01	
125	.75	.52	.25	.09	.02	.01
150	.87	.68	.45	.20	.07	.02
175	.96	.82	.58	.32	.12	.03
200	.98	.93	.80	.52	.26	.09

Maximum Snow W.E. 188% Max Peak Flow 200%

Based on Wolf Creek Pass Snow Course

Note: This stream has enough storage to control up to 4000 - 5000 cfs of natural flow. It is used as indicated for reservoir filling needs and sometimes for flood control. Some adjustment of data was attempted but full adjustment is impractical. Standard deviations are high--25% of average flow.

XXIX. --Probability of exceeding a specified flow in percent of average if snow water equivalent is a specific percent of average--Conejos near Mogote, 1936-67.

Feb. 1 Snow W. E. % Avg.	Peak Runoff in Percent Avg. 100	125	150	175	200
100	.80	.40	.10	.01	
125	.90	.55	.20	.02	.01
150	.98	.76	.33	.05	.01
175	.99	.88	.49	.10	.01
200	.99	.96	.73	.20	.02
225	.99	.99	.87	.45	.08
250	.99	.99	.93	.50	.12

Maximum Snow WE 220% Avg. Max. Peak Flow 188% Avg.

Apr. 1 Snow W. E. % Avg.	100	125	150	175	200
100	.70	.25	.02	.01	
125	.90	.50	.12	.01	
150	.98	.75	.30	.02	.01
175	.99	.90	.50	.10	.01
200	.99	.98	.70	.30	.03

Maximum Snow WE 195% Avg. Max. Peak Flow 188% Avg.

Based on average of Summitville and Wolf Creek Pass Snow Courses.

Note: Since 1950 stream has been subject to substantial regulation.

F. Atmospheric Water Balance

1. Introduction

Comparisons of atmospheric water vapor flowing out of the volume over a land area with that which entered the volume can be used to estimate the amount of water left behind as precipitation or picked up through evaporation.

The concept of the atmospheric water balance and its usefulness in hydrometeorological applications is well known (e. g., Benton and Estoque, 1954; Hutchings, 1957; 1961; Rasmusson, 1966; and Palmén, 1967). In particular the atmospheric water balance has been computed for the Upper Colorado River by Rasmussen (1968). The results of the last work show that the annual discharge of the river is highly correlated with the accumulation of water over the basin during winter where the accumulation is determined using the atmospheric water balance technique. The techniques of atmospheric water balance are being prepared to evaluate their potential as an evaluation tool or as an operational aid for the large scale cloud modification operation over the Upper Colorado Basin.

These techniques may have the advantages of:

a. Providing good Basin-wide estimates of precipitation and evaporation. In a properly designed experiment it should be possible to determine the portion of the precipitation resulting from weather modification efforts.
b. Using data from present radiosonde stations supplemented by a few additional stations to provide almost continuous determinations of precipitation without the aid of a great number of expensive and difficult-to-maintain ground observing stations.
c. Providing a system for continuously accumulating integrated total Basin precipitation and at the same time defining the accumulated increment from weather modification efforts.
d. Providing a superior system for describing Basin streamflow by allowing a systematic description of the accumulations and losses of both natural and artificial increments of water.
e. Providing a forecast tool of natural and artificial precipitation potential for use in planning field operations.

This section outlines progress to date in the exploration of these techniques.

2. The Atmospheric Water Balance as an Evaluation Technique for Weather Modification Operations

The atmospheric water balance can be solved to yield the quantity P - E, precipiation minus evaporation, as a computational residual. The equation

$$P - E = -\frac{1}{g}\iint \frac{\partial q}{\partial t}\, dp\, dA - \frac{1}{g}\iint C_n q\, dl\, dp - \frac{1}{g}\iint \frac{\partial s}{\partial t}\, dp\, dA - \frac{1}{g}\iint C_n s\, dl\, dp$$

is the atmospheric water balance equation. The integrals are approximated by finite computational steps and are solved numerically using radiosonde data (see, for example, Rasmussen, 1968). Here q is specific humidity, s is the mass of liquid water per mass of air, p is pressure, g is gravity, A is horizontal area, Cn is the wind component normal to the side of the volume defined positive away from the basin, and dl is an increment of horizontal distance on the wall of the volume.

In practice one must deal only with the balance of water vapor and neglect the liquid water terms of the above equation because only water vapor is sampled. This restriction could be source of error for the case of orographic clouds since the clouds would exist on one portion of the boundary. This situation would yield a biased computation toward positive P - E since the advection into the area would be in the vapor phase and the advection out of the area in the water or ice phase. Further discussion of the limitations of the technique will be covered later in this section.

The P - E value is the total rate of water mass exchange at the earth's surface over the area of study. This quantity accumulated over a suitable period, then, is the yield of the atmosphere for that area for that period of time. Under a successful weather modification program an increase in this yield should be observed. Because of the inaccessibility of much of the area to be treated, particularly during winter, the problem of accurately determining precipitation with gages is practically impossible. The atmospheric water balance technique is therefore an attractive alternative to the direct measurement. The question of how one may use the method for the evaluation is dependent upon the operational design.

a. An operation designed to include a randomization of seed - no-seed days.

   For this case the statistics of the P - E results for the two classes, seed-no-seed may be tested to determine if a significant change has been imposed. This evaluation can include any area of the basin that has been sufficiently observed. The addition of rawinsonde stations certainly is a necessary condition to the successful completion of this computation.

b. An operation designed to seed all possible precipitation events.

   For this case the problem of evaluating the net benefit of the operation is more difficult. We have determined the relationship between annual runoff and accumulation during winter over the <u>entire</u> Upper Basin for the years 1957-1963 (Rasmussen, 1968). The runoff is largely derived from snow melt over the small percentage of area above 9,000 ft msl. The weather modification operation will be conducted only over this same area above 9,000 ft msl. Little effect due to modification should be noted over the region below 9,000 ft msl and the percent increase in precipitation yield over the total basin will be relatively small, but the increase in runoff relatively large. We, therefore, should expect a shift in the winter P - E versus annual runoff relationship to be as depicted in Figure 64.

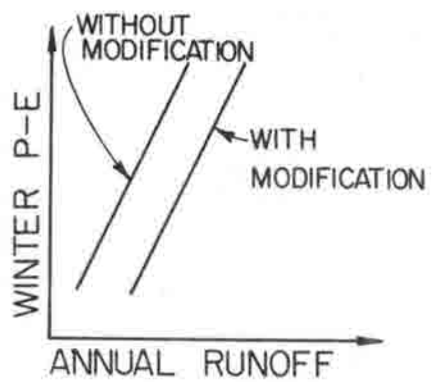


Figure 64. --Sense of the anticipated shift in the P - E versus R.O. relationship due to cloud modification.

This possible evaluation procedure can be tested without reliance on increased observations. It is necessary, however, to modify large enough portions of the watershed such that the change in runoff from the basin will be significant.

3. The Atmospheric Water Balance as a Tool in the Daily Weather Modification Operations

Let us assume that special observations are available so that the wind, humidity, temperature and pressure (or height of pressure surfaces) on the vertical boundaries of the area over which the weather modification is to be affected. One can use this information to obtain the distribution of rate of condensate as a function of pressure and/or temperature. In a recent paper by Rasmussen, Furman and Riehl (1969) a use of such an analysis procedure is demonstrated for a moving cyclone. The procedure, in brief, is as follows: The air circulating through the system is assumed to conserve its equivalent potential temperature (θ_e), this is the same as assuming the sum of the sensible and latent heat remains constant following the air parcel. This assumption does allow for any outside source or sink of energy (e.g., radiation) and further it is assumed that any condensate formed is removed immediately from the air parcel. Each data point on the boundary of the volume then has air with a certain equivalent potential temperature and this air is either streaming into or out of the volume. Upon integration over the whole volume then the three dimensional mass flow for the various θ_e values are known and the rate and location of condensate formation is determined by following the air through the various θ_e channels. Figure 65 shows a two-dimensional picture of the flow from Grand Junction over Chalk Mountain and to Denver for one day in December, 1968. The picture shows the air with equal θ_e values to describe a path roughly parallel to the topography near the surface and becoming almost horizontal at 500 mb. This type of analysis can be

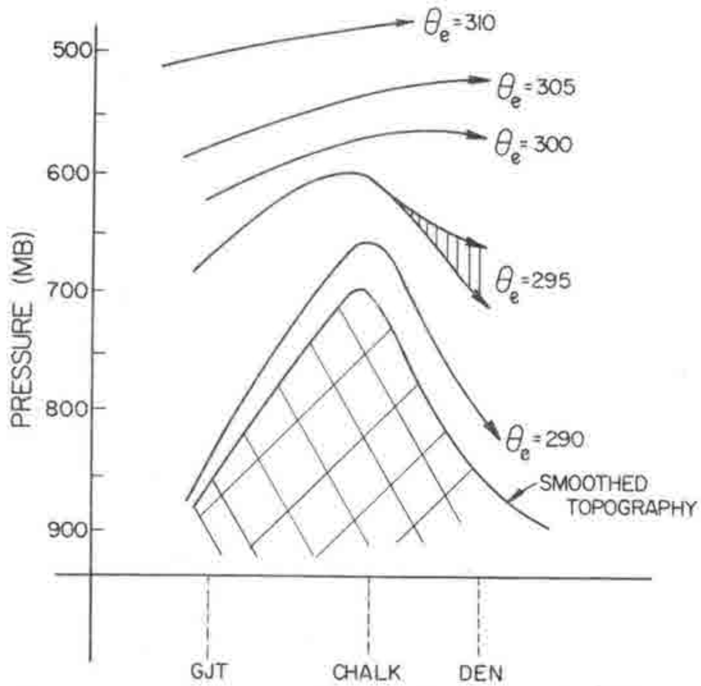


Figure 65. --θ_e crossection for (θ_e values in °K), Grand Junction, Chalk Mountain, Denver, for December 6, 1968, a precipitation occurrence at Chalk with west winds. Section approximately shows the flow up and over the Continental Divide.

extended to determine the moisture flow in the various θ_e channels and the rate of condensation profile can be determined from the initial temperature and humidity values. This information would be most useful in the design of the operational model since the cloud location and temperature is of such paramount importance to the success or failure of the daily operation. A study of this nature for the Colorado Rockies is underway currently.

4. The Limits of the Water Balance Technique

General drawbacks to the atmospheric water balance technique are apparent

a. Sampling errors caused by
   (1) Too widely spaced data points
   (2) Too infrequently taken observations
b. Instrument errors in the measurement of the wind, temperature and humidity values
c. The problem of not sampling the liquid water or ice; only the water vapor is sampled.

The work of Hutchings (1957) is a classic in the error analysis of the atmospheric water balance. His work is for southern England during summer but the gross result should be expected to hold for the Upper Colorado River Basin during winter. The standard error in divergence of water vapor transport is on the order of 1.3 gm/cm^2 per month using four rawinsonde stations sending twice daily ascents. Note should be taken that this error is approximately 50% of the total divergence of flux calculated by Hutchings; however, the standard error should not increase as the total increases and so, during winter over the Upper Colorado, this amount of error is of a much smaller percentage. Of this error, about 90% is due to the sampling error and 10% due to the systematic and random instrument errors. Thus, in order to improve the accuracy of the technique, and to make maximum use of the rawinsonde instruments, one should increase the density and frequency of observations. In order to statistically evaluate the particular sampling errors for the Upper Colorado a series of rawinsondes at various lag times should be obtained. Ascents from every hour through every twelve hours should be tested for auto correlation coefficients that will lead to an estimate of the sampling error under various experiment designs. An appropriate statistical model for the sampling error could be:

$$\varepsilon^2 = \frac{b^2}{n}\left[\frac{1+\rho}{1-\rho} + \frac{2}{\ln \rho}\right]$$

where ε is the standard sampling error, b the standard derivation and ρ the auto correlation coefficient (Cochran, 1946; Hutchings, 1957). The auto correlation coefficient is assumed exponential in this model and there is sufficient evidence that such is the case for rawinsonde data. Rasmussen (1968) showed error due to the neglect of the divergence of flux of liquid water is small for the whole Colorado River Basin. However, as the area becomes smaller the relative contribution of this term will increase in importance. If one chooses, as an extreme case, a non-precipitating cloud, 5 km thick (assume a density of .1 gm/m^3) and let it extend along one boundary of the basin for 100 km the amount of water transported out of the basin by an invarient wind of 10 meters per second would be .05 cm of water per day distributed evenly over the area of a basin 10 km wide extending the length of the cloud. This value is only about 10% of the average precipitation observed per precipitation day so the error in neglect would not be appreciable.

A good guideline appears to be that, in any event, a minimum of four rawinsondes having twice daily ascents is necessary to give a P - E value with 10% of the expected total precipitation of 30 days operation . Accurate daily values will require more observations but no information on the structure and variability of the atmosphere over the Upper Colorado on such short time and distance scales using rawinsondes as sampling devices is available. This study should be carried out at the earliest possible time so that a truly representative error analysis can be performed.

G. Statistical Design and Evaluation Procedures

The natural variation in precipitation events necessitates the use of statistical techniques to establish the alterations resulting from weather modification efforts. In a research type program, statistical techniques are essential for evaluation and interpretation of the treatment. In an applied program statistical analyses are required to discriminate between the natural and artificial increments. The initial design of a field program determines the type of statistical procedures which can be employed. Application of the best statistical techniques requires that restrictions be made on seeding by leaving an adequate number of randomly selected periods unseeded. This restriction can be particularly undesirable in an applied program since a number of good opportunities for augmenting water supplies are lost. Since the pilot project for the Colorado River Basin is intended as a transition from experimental to applied programs in weather modification, it is necessary to consider design features suitable for experimental programs and also suitable for the incorporation of applied programs. This, however, presents many problems. The following discussion presents some of the more important aspects being considered for the statistical design.

1. Levels of Control and Lengths of Sampling Unit

While weather modification efforts in a pilot project in the Colorado River Basin will aim at increasing precipitation, the desired objective is increased streamflow. The ultimate worth of the program must consequently be evaluated in terms of water produced. Therefore, if at all feasible, direct evaluation of changes in streamflow are desirable. Unfortunately, an optimal design for emphasizing evaluation of precipitation is not at all optimal for emphasizing evaluation of streamflow. As a consequence, a trade off is necessary for satisfying both types of evaluation to any reasonable extent.

The area of operation which appears to have the greatest chance of showing a significant streamflow effect is the San Juan area. It is estimated that a full scale operational seeding program in the San Juan area (based on the present state of the art) using ground generators might produce increases of the order of 30% in total streamflow. Historical annual streamflow correlations between the San Juan area and the Aspen area in central Colorado are about .85 (Morel-Seytoux, 1968). If the Aspen area is used as a control area, increases of streamflow in the San Juan area of 30%, 18%, 15%, and 10% could be detected at the 5% level with about 90% power in 2 years, 5 years, 7 years, and 15 years, respectively. Optimal evaluation in terms of streamflow requires that operational seeding be done for all opportunities in order to maximize total increases.

On the contrary, optimal evaluation in terms of precipitation can utilize unseeded periods randomly interspersed with seeded periods. One vital consideration in connection with seeded and non-seeded events is the length of the sampling unit.

The Climax experiment (Grant and Mielke, 1967) utilized a sampling unit of 24 hours with a great deal of success in its nine years of operation. The 24-hour unit appears to be sufficiently long that confounding contamination problems involved with seeding are not severe. Also the 24-hour unit is short enough that adequately defined meteorological descriptions are possible. Finally, the 24-hour period is not affected by any diurnal variation which might otherwise be a problem. Based on these considerations, the 24-hour period (event) has many advantages for evaluation of weather modification efforts, particularly when using ground seeding techniques.

2. Randomization

Optimizing criteria for evaluation using either precipitation or streamflow could be met if one could seed all events for two randomly selected years and leave all events non-seeded during two cont control years. However, this procedure requires that the distributions of precipitation under the physically partitioned sets of events be about the same during the two optimally seeded years as during the two non-seeded control years. This question was dealt with using seven historical years of precipitation data available for the San Juan area at Wolf Creek Pass. Physically partitioned sets of 24-hour intervals, based on 500 mb temperature partitions was obtained and precipitation data was compared among the seven years as a whole and under three temperature partitions as shown in Figures 66, 67, 68, and 69. Figure 66 is for 24-hour precipitation amounts for the respective years using all cases without any temperature categorization. Figures 67, 68, and 69 show the 24-hour distribution of precipitation for the following temperature categorizations: (1) T≥-20C (favorable for seeding), (2) -20C>T≥-23C (questionable for seeding), and (3) -23C>T (unfavorable for seeding), respectively.

Visual analyses of these figures illustrate that nature does not in fact deal out the same type of precipitation pattern year after year under the three 500 mb temperature partitions. This is particularly true for the all-important warm temperature partition given in Figure 67. As a consequence, if precipitation analyses were in fact considered to be of prime importance, it appears that an investigator must utilize randomization within each year of operation.

Assuming precipitation amounts at specific locations could be precisely predicted from concomitant information, the effects of cloud seeding could be obtained deterministically, for each location. Unfortunately, such predictions are not possible and, as a result, the effects of cloud seeding must be evaluated stochastically. As a consequence, seeded and non-seeded events must be randomly allocated within annual periods to achieve sound comparisons. Another point pertaining to randomization within annual periods is that randomized blocks of say 20 to 40 events should be employed in order to insure balance over all seasons of the operation. In particular, if a block of 30 events was utilized and 60% of the events were to be seeded, then 18 and 12

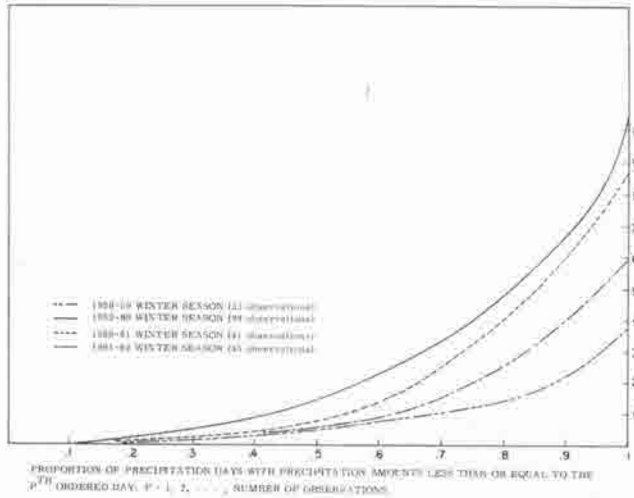


Figure 66.--Precipitation at Wolf Creek Pass during four winter seasons (from November 1 through April 30).

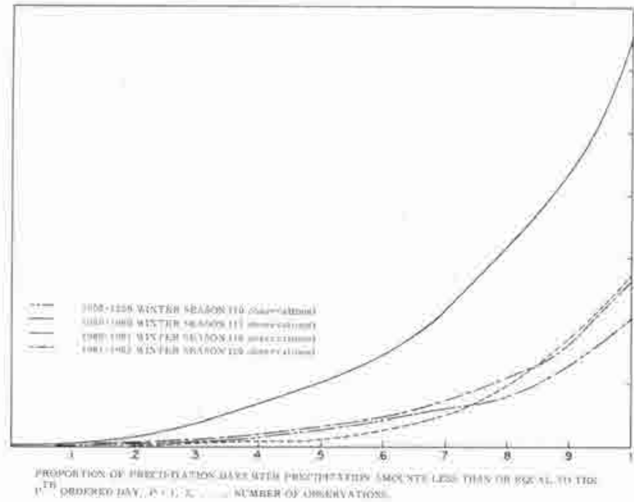


Figure 67.--Precipitation at Wolf Creek Pass for 500 mb temperature greater than -21° C during four winter seasons (from November 1 through April 30).

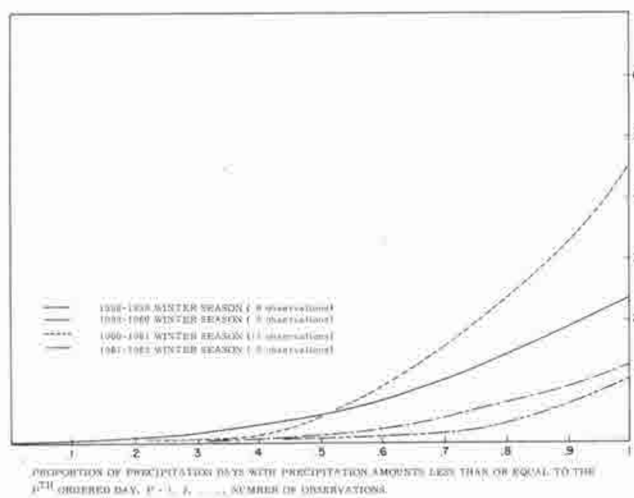


Figure 68.--Precipitation at Wolf Creek Pass for 500 mb temperature greater than -24° C and less than or equal to -21° C during four winter seasons (from November 1 through April 30).

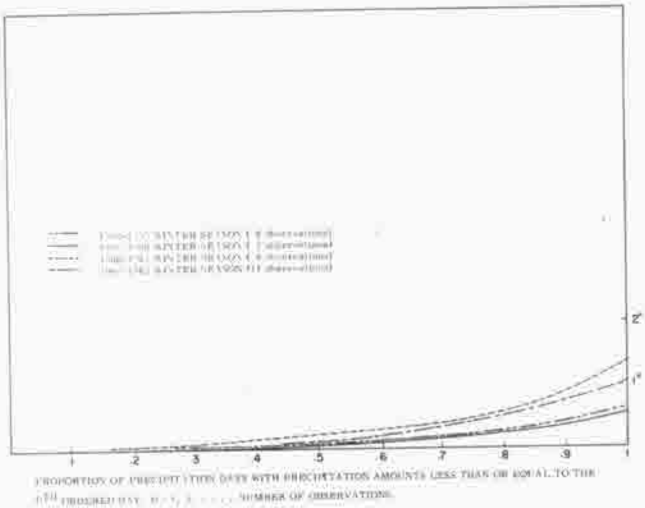


Figure 6. . recipitation at Wolf Creek Pass for 500 mb temperature greater than -27° C and less than or equal to -24° C during four winter seasons (from November 1 through April 30).

of 30 events would be seeded and non-seeded, respectively. Also the seeded and non-seeded events would be placed in a random order.

If the randomization scheme during each year of operation includes seeding during 50% and 60% of the events, the change could be detected at the 5% level with about 90% power in 7 years and 5 years, respectively, if an actual increase of around 30% could be achieved with seeding during 100% of the operationally defined events. Furthermore, streamflow analyses is a step removed from modification of clouds and does not permit physical interpretation of the treatments applied. Therefore, analyses of precipitation complimented by a procedure to convert precipitation data results to streamflow results appears to be another important consideration to be developed.

Providing an adequate number of years would be available for this operation, then sampling units consisting of year-long intervals would certainly be satisfactory. Sampling units consisting of year-long intervals would not be appropriate for a pilot program as short as four years.

The proportion of seeded to non-seeded events also need careful consideration. Suppose p is the proportion of seeded events to non-seeded events. Then, under a null hypothesis that seeding is of no value, the large sample test statistics (parametric and non-parametric) used for evaluation will be approximately distributed as the normal distribution with a mean of zero and a variance proportional to $[p(1-p)]^{-1}$. Thus the standard error of such a test is proportional to $1/\sqrt{p(1-p)}$ which is minimized at $p = \frac{1}{2}$. However, since $1/\sqrt{p(1-p)}$ is very flat for p in the vicinity of $p = \frac{1}{2}$, any of the tests will not lose much power in this vicinity of p for a large fixed number of seeded and non-seeded events. Unfortunately, in small partitions of the randomly selected seeded and non-seeded events (i.e., particular partitions chosen for their physical characteristics), the previous argument is not as appropriate. The hope would be to maintain a balance in the partitioned samples when the only enforced balance was applied to the total of seeded and non-seeded events considered. The best chance of having reasonable balance occur in the respective partitioned samples when $p = \frac{1}{2}$.

3. Statistical Techniques

Analyses of the resulting precipitation data of the pilot project should involve the use of both parametric and nonparametric approaches. Appropriate parametric techniques would include simple regression analyses using gamma transformations (Thom, 1957) and distribution and effect dependent optimal tests (Neyman and Scott, 1965). Nonparametric techniques such as the two-sample Wilcoxon and sum of squared ranks tests (Mielke, 1967; Duran and Mielke, 1968) should be used. Assuming differences in seeding result in scale changes, Duran and Mielke (1968) have shown that the sum of squared ranks test has excellent large sample properties for a broad class of distributions which appear to closely approximate actual precipitation distributions. Multivariate techniques should be investigated more in the future to see if even more powerful robust techniques can be developed. Univariate and multivariate regression approaches should be applied in the analyses of streamflow data resulting from the pilot project (Morel-Seytoux, 1968).

4. Data Collection

The number and location of data sensors can substantially affect statistical analyses. A recent study of the Climax experiment (Mielke, et al., 1970) illustrates that large differences in the effect of seeding are a function of both location relative to the target area and altitude. This study also indicates that individual stations which are close to one another are remarkably consistent in contrast to what has been noted with summertime convective cloud studies. As a result, it appears that sensors should be placed at different altitudes with the emphasis on the higher altitudes since this is where most of the snowpack will occur. Another feature which would be desirable would be to have paired sensors at well-placed locations for making internal verifications. This may not be feasible at all sites but should be done at some well-scattered locations over the network.

H. Weather Modification Economics

1. Introduction

The need for research on the economic and social aspects of weather modification has been emphasized numerous times.[1] Authors rarely fail to note that in spite of this need, few, if any, systematic and comprehensive studies have been made. Economic research should accompany and be an integral part of the program of physical research on weather modification. Without appropriate economic analyses there can be little assurance that any system of modifying weather is economically feasible, efficient, and equitable to all affected private and public interests. Such considerations are an essential aspect of the Colorado River Pilot Project, which has as one of its ultimate goals the economic production of additional water supplies. Any adaptation and comprehensive application of techniques of economic analyses to the Colorado River Pilot Project should also increase knowledge of how to adequately assess the economic and social consequences of other weather modification endeavors.

The general research objectives of the design study are to: (1) Explore, rank, and measure the economic consequences of weather modification, taking both benefits and costs into account; and (2) Evaluate economic attributes of alternate methods of weather modification in relation to probability variation inherent in various techniques. Although more than economic factors are critical to decisions concerning weather modification, it is helpful to consider economics in both the above-noted problem areas. Trade-off prices can be established for options selected or rejected, and in this way more fully guide future research policy and public action.

The economic aspects can be categorized as follows:

a. Direct impacts (e.g., water availability)
b. Social impacts (e.g., effects on human activities, recreation, etc.)
c. Private impacts (e.g., moisture for the ranchers in the area)
d. Non-economic impacts (e.g., transportation hazards)
e. Indirect impacts (e.g., the effects on forest production)
f. Quality impacts (e.g., quality of the water)

Irrespective of the classification of a given impact, it is also necessary to rank the numerous consequences of modification by probable or possible levels of importance to modification efforts, research, and future policy. A three-stage ranking of significance as primary, secondary, and tertiary, can readily be considered for this purpose.

First-order considerations might include such items as:

a. Changes in water production of the basin
b. Snowpack changes that would affect the ski industry
c. Precipitation changes that would affect the resort industry
d. Domestic water supplies
e. Carryover water into the summer season and the subsequent winter
f. Alterations in the stability of streamflow characteristics; e.g., peak flow versus volume flow
g. Social disruption
h. Highway interference
i. Air travel
j. Etc.

Second-order considerations might include such items as:

a. Changes in forest fire hazards
b. Effect on livestock
c. Atmospheric pollution
d. Industry
e. Cropped agriculture
f. Effects on overhead
g. Forest effects; e.g., altered growth cycle
h. Changes in sedimentation
i. Utilization of additional water supplies and indirect effects on economy

Third-order considerations might include such items as:

a. Erosion
b. Wildlife
c. Ecological changes
d. Forest effects, such as change in insects problems
e. Changes in forest tree species
f. Secondary effects on runoff from change in vegetation
g. Effects on temperature

2. Objectives

While such potentially important economic aspects can be defined, their analyses is beyond the scope of the design study for the Colorado River Pilot Project. Certain economic aspects, however, must be explored, since they have a direct bearing on design and operational alternatives.

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[1] See, for example: Ackerman, Edward S., "Design Study for Economic Analysis of Weather Modification in U.S." Advisory Committee on Weather Control, Final Report, (Washington, D.C.: U.S. Government Printing Office, 1957) Vol. II, pp. 233-245; Gilman, Donald L., Hibbs, James R. and Laskin, Paul L. "Weather and Climate Modification--A Report to the Chief, United States Weather Bureau," (Washington, D.C.: U.S. Department of Commerce, 1965) pp. 19-26; "Weather and Climate Modification," Report of the Special Commission on Weather Modification, (Washington, D.C.: National Science Foundation, 1966) pp. 80-90; and Sewell, W.R. Derrick "Introduction: The Problem in Perspective" in Human Dimensions of Weather Modification, University of Chicago, Department of Geography Research Paper No. 105, (Chicago, Illinois: University of Chicago Press, 1966) pp. 1-16.

These include (1) a general definition of the economic value of additional water resulting from modification systems, (2) delineation of the more critical negative benefits of weather modification, and (3) cost-analysis systems to allow for future cost effectiveness comparisons of alternative modification techniques, given varying probabilities of program success.

3. Procedures

Primary pilot project design efforts during the first year have been concentrated on the physical aspects of the program. Steps have been taken to outline the economic aspects of the program as presented above. Analyses to explore cost-benefit relationships with various treatment methods are getting underway. General estimates of cost-benefit ratios presented by Grant (1967) at the Second Skywater Conference point up the importance of these considerations. It was estimated in that paper that an area along the Continental Divide extending for 30 miles could reasonably expect to develop additional water from weather modification worth about $80 per hour if water is valued at $5 per acre-foot and precipitation is increased 20%. If precipitation is increased about 100% for storms with clouds warmer than -20° C (See V,B above), the average value of water produced from these cases could exceed $400 per hour. These calculations, while of a general nature, do show that, for economic production of water, techniques that can cover 30 mile stretches of the mountain areas at costs of no more than several hundred dollars per hour (including overhead) should be considered.

4. Possible Effects of Precipitation Modification on Selected Watershed Parameters

The effects of modified precipitation on selected watershed management parameters has been explored by Rango (1969) with partial support from the hydrologic and economic analysis portion of the design program for a pilot project in the Colorado River Basin. Progress in this effort is described below in abstracted form as prepared by Rango.

> A presumptive approach was used to analyze the effect of precipitation modification on selected watershed parameters. Increased mean annual precipitation was assumed and the resultant changes of runoff, stream channel geometry, sediment yield, and vegetation weight were predicted. The techniques used for prediction involved either adapting existing methods to the specific problem or collecting data in the field and from published sources in order to develop regression equations, which were manipulated to simulate changes as a result of precipitation modification.
>
> The techniques employed were tested primarily on small watersheds near Newell, South Dakota, and Grand Junction, Colorado.
>
> 1. When precipitation increases were simulated, it was apparent that the percentage runoff increase could be two to four times as great as the percentage precipitation increase.
> 2. It was found that some significant changes could occur in stream channel geometry as a result of increasing precipitation, and that some of these changes were different from what would be expected on large watersheds.
> 3. Regression analysis of sediment yield-precipitation data indicated that sediment yield on small watersheds would increase with increasing precipitation until about 27 inches mean annual precipitation. At this value increased vegetation cover and weight would tend to decrease sediment yield with further increases in precipitation. The most pronounced increases in sediment yields as a result of precipitation augmentation will probably occur in arid regions.
> 4. The probable vegetation weight increase from an assumed 15% precipitation increase in arid and semi-arid regions was 25 - 30%. Comparable percentage changes in the above parameters as a result of simulated precipitation modification on high elevation, more humid watersheds will probably be less pronounced.
>
> It appears that the techniques employed in the study can be used for obtaining an estimate of whether precipitation modification will be beneficial or detrimental to watersheds in a specific area.

5. Snow Inconvenience Indices for the Red Mountain-Coalbank Hill Area

Since snow removal may present a problem in the pilot project, an exploratory-type analyses has been made to determine the feasibility of establishing snow inconvenience indices. This work has been carried out for the Red Mountain-Coalbank Hill area.

Since 1962, the Colorado State Highway Commission has kept cost records by work assignments for each maintenance district. Among the breakdown of costs are snow removal, avalanche control, snow fence repair and highway sanding. Costs used in this report include snow removal, avalanche control and snow fence repairs. Except for sanding, snow removal represents over 90% of the costs related to snow. Sanding of highways bears little relation to total snowfall and includes costs outside of mountain areas. Sanding costs are relatively constant on an annual basis with variation only in extreme years. The costs in this study were for the Grand Junction and Durango districts, both concerned with maintenance in the Red Mountain-Coalbank Hill area.

These costs do not include replacement of new equipment which is part of other highway maintenance functions. They do include direct costs of personnel, maintenance and operations, and apparently an allotment of district overhead costs.

These data allow the comparison of a snow removal cost index to a snow inconvenience index, and gives some indication of the variation in costs of having to deal with snow on the ground. This study indicates that there is an annual cost of having a minimum snowfall of about 50% of costs in a near maximum snow year. After these minimum or overhead costs have been met, the snow inconvenience factor varies almost directly with the amount of snowfall. From the limited seven-year record, it appears that the snowfall may be indexed in a number of ways with near comparable accuracy. However, the indices to be preferred from both a practical and statistical standpoint for the period 1962-1968 approximates the following order.

a. Snow water equivalent on snow courses
b. Depth of snow on the ground
c. Total seasonal snowfall as it falls
d. Total seasonal snowfall as it falls in storms in excess of three inches
e. Total seasonal snowfall as it falls in storms in excess of six inches
f. Number of storms in excess of three or six inches (a much poorer index than the first five)

In reference to item f, storms in excess of six inches typically occur less than five times in a season. The occasional two to three foot storm which closes the road is an extreme temporary inconvenience but does not materially affect the total seasonal cost.

a. Adjustment of cost indices

Because of constantly increasing cost indices, it is necessary to make some adjustment in comparing actual costs over a seven-year period. Figure 70 shows the approximate total costs of highway maintenance in Colorado from 1960 through 1967 by years. The actual total cost of highway maintenance in 1967 was 135% of that for 1960. (Note that costs tended to rise more rapidly in 1962, 1965 and 1968, which may reflect to some degree the high snow removal costs in those years).

While it is reasonable to expect that total maintenance load increased over this period, it is also reasonable to assume that state and local government costs have increased more rapidly than the general cost index in recent years. Regardless of the merit of the judgment used, the actual costs for the various years were increased (based on 1967 as 100) by a percentage as indicated in Figure 70. This is an inverse relation to the increase in maintenance costs.

The cost index adjustments are shown in Tables XXX and XXXII for the Durango and Grand Junction Districts, respectively.

b. Assignment of proportion of costs for districts to Red Mountain-Coalbank area

The Durango district covers highways to the summit of Wolf Creek Pass, the summit of Red Mountain Pass, and over Lizard Head Pass. These are the areas where major snow removal is required within the district. The annual snowfall in the three areas are highly related. Therefore, on the basis of highway mileage where extensive snow removal is required, 50% of the total adjusted snow removal costs for the Durango district was assigned to the Red Mountain-Coalbank Hill area.

The assignment of costs to this area for the Grand Junction District is more complex. The major snow removal areas are widely separated at Vail Pass, Tennessee Pass, Monarch Pass and Red Mountain Pass. There is a relatively greater mileage of highways at medium elevations where some snow has to be removed.

Snow courses in these areas were selected to represent snow removal needs indices. The proportion of costs assigned to the Red Mountain area was based on the ratio of the snow water equivalent index on Ironton Park snow course to the total of snow water equivalent indices at Ironton Park, Crested Butte, Tennessee Pass and Shrine Pass snow courses. It would be expected that the estimate of costs for this district would be subject to more error than for the Durango district because of the procedure used and the amount of low elevation snow removal in the district. However, the final comparisons do not indicate that this is necessarily true. The development of these indices is shown in Tables XXXII, XXXIII, and XXXIV.

c. Snow removal needs indices

For both the Durango and Grand Junction districts, snow removal needs indices were developed from applicable snow course data in the area. The Spud Mountain (elevation 10,700) snow course was used for the Durango District and the Ironton Park (elevation 9,800) snow course was used for the Grand Junction District. Other indices could have been used since data on snow water equivalent, total seasonal snowfall, and snowfall on the ground, measured at stations in the area are highly correlated.

Snow removal in mid-winter is more difficult than during late winter and early spring. Days are shorter in mid-winter, working conditions are more adverse, and there is little help from warm temperatures. Several adjustments to actual snow equivalent data were tried. It appeared most logical to assign a weight of 1.50 to snow accumulation up to February 1, a weight of 1.25 to snow accumulation or depletion during February, 1.00 for the same in March, and 0.50 to the same for April. Snow removal after May 1 was ignored as a minor factor. Algebraic signs were used to calculate increases or decreases in snow water equivalent in the months involved.

TABLE XXX. -- SNOW REMOVAL COSTS - DURANGO DISTRICT

Year	Total	Adj.	Personnel	Adj.	M. and O.	Adj.	Cost Index Factor	Estimated Cost to Red Mt. Area
1962	126	158	77	95	49	61	125	79
1963	101	121	66	79	35	42	120	60
1964	98	113	66	76	32	37	115	56
1965	173	190	122	134	51	56	110	95
1966	139	146	96	102	42	44	105	73
1967	129	129	64	64	65	65	100	64
1968	158	150	85	81	73	69	95	75

Costs for snow removal in $1,000 does not include sanding.
50% of District costs assigned to Coal Bank - Red Mountain Area
From Fiscal Year Comptroller's Reports, State Highway Commission

TABLE XXXI- SNOW REMOVAL NEEDS INDEX - COAL BANK - RED MT. AREA (DURANGO DISTRICT)

(Spud Mt. Snow Course)
(Snow Water Equivalent)

Year	Feb. 1	Adj.	Feb. Inc. or Dec. Act.	Feb. Inc. or Dec. Adj.	Mar. Inc. or Dec. Act.	Mar. Inc. or Dec. Adj.	Apr. Inc. or Dec. Act.	Apr. Inc. or Dec. Adj.	Total Index
1962	29.0	43.5	12.2	15.2	1.7	1.7	-4.5	-2.2	52.7
1963	14.5	21.7	5.5	6.9	3.7	3.7	-2.8	-1.4	25.7
1964	8.1	12.0	1.2	1.5	7.9	7.9	2.9	1.4	22.8
1965	27.1	40.5	4.0	5.0	3.0	3.0	6.5	3.2	58.2
1966	24.2	36.3	6.2	7.8	-3.8	-3.8	-2.2	-1.1	39.2
1967	19.0	28.5	0.9	1.1	-0.9	-0.9	-3.5	-1.7	27.0
1968	19.2	28.8	4.0	5.0	4.0	4.0	2.2	1.1	38.9

Adjustment factor to Feb. 1 - 1.50, Feb - 1.25, March- 1.00, April - 0.50

TABLE XXXII- SNOW REMOVAL COSTS - GRAND JUNCTION DISTRICT

Year	Total	Adj.	Personnel	Adj.	M. and O.	Adj.	Cost Index Factor	Cost for Red Mt. Area
1962	169	211	92	115	77	96	125	42
1963	128	154	74	89	54	65	120	31
1964	165	190	96	109	71	81	115	52
1965	205	226	140	154	65	72	110	40
1966	171	180	111	117	60	63	105	32
1967	207	207	109	109	98	98	100	37
1968	192	182	106	101	86	81	95	55

TABLE XXXIII- SNOW REMOVAL NEEDS INDEX - RED MT. - OURAY AREA

(Grand Junction District)
(Snow Water Equivalent)

Year	Feb.1	Adj.	Feb. Inc. or Dec Act.	Feb. Inc. or Dec Adj.	Mar. Inc. or Dec. Act.	Mar. Inc. or Dec. Adj.	April Inc. or Dec. Act.	April Inc. or Dec. Adj.	Total Index
			Ironton Park Snow Course (Red Mt. Area)						
1962	9.5	14.1	3.1	3.9	1.6	1.6	-7.4	-3.7	15.9
1963	4.3	6.5	5.7	7.1	0.2	0.2	-10.2	-5.1	8.7
1964	6.9	10.3	3.3	4.1	5.6	5.6	-2.0	-1.0	19.0
1965	10.1	15.1	2.2	2.8	5.6	5.6	-9.5	-4.7	18.8
1966	8.2	12.3	1.3	1.6	-4.3	-4.3	-5.2	-2.6	7.0
1967	7.3	11.1	3.5	4.4	-3.1	-3.1	-3.3	-3.3	9.1
1968	8.2	12.3	6.5	8.1	1.2	1.2	1.6	0.8	22.4

TABLE XXXIII Continued:

Year	Feb. 1	Adj.	Feb. Inc. or Dec. Act.	Adj.	Mar. Inc. or Dec. Act.	Adj.	April Inc. or Dec. Act.	Adj.	Total Index
Crested Butte Snow Course (Gunnison - Blue Mesa - Monarch Pass Area)									
1962	9.3	14.0	5.6	7.0	4.9	4.9	-10.0	-5.0	21.0
1963	3.3	5.0	5.0	6.2	3.5	3.5	-11.8	-5.9	8.8
1964	5.3	8.0	0.4	5.2	5.2	5.2	1.4	0.7	14.4
1965	13.3	20.0	3.0	3.8	5.6	5.6	2.5	1.2	30.6
1966	7.9	11.8	1.9	2.4	-1.3	-1.3	-8.5	-4.2	8.7
1967	8.1	12.2	3.6	4.5	1.3	1.3	-12.0	-6.0	7.0
1968	7.9	12.0	3.7	4.6	2.2	2.2	-2.7	-1.4	17.4
Tennessee Pass Snow Course (Eagle - Tennessee Pass Area)									
1962	8.5	12.3	3.2	4.0	1.1	1.1	-3.5	-1.7	11.1
1963	5.0	7.5	2.1	2.6	1.3	1.3	-5.4	-2.7	8.7
1964	3.9	5.9	1.2	1.5	3.1	3.1	1.8	0.9	11.6
1965	9.8	14.8	3.9	4.9	2.8	2.8	-3.0	-1.5	20.0
1966	6.6	10.0	-0.2	-0.2	-0.4	-0.4	-1.0	-0.5	8.9
1967	7.9	11.9	1.4	1.7	0.8	0.8	-7.5	-3.8	9.6
1968	5.9	7.4	3.3	4.1	0.2	0.2	1.1	0.5	13.3
Shrine Pass (Minturn - Vail Area)									
1962	16.0	24.0	4.5	5.6	-0.7	-0.7	3.3	1.6	30.5
1963	5.3	8.0	5.4	6.7	2.8	2.8	-1.9	-1.0	16.5
1964	6.4	9.6	2.9	3.6	6.1	6.1	2.4	1.2	20.5
1965	11.4	17.1	5.6	7.0	7.1	7.1	0.5	0.2	31.4
1966	7.3	11.0	2.2	2.7	0.8	0.8	-0.7	-0.3	14.2
1967	10.0	15.0	5.1	6.4	2.0	2.0	1.8	0.9	24.3
1968	8.5	12.6	6.2	7.7	2.1	2.1	3.7	1.9	24.3

Adjustment factor to Teb 1 - 1.50, Feb. - 1.25, Mar. - 1.00, Apr. - 0.50

TABLE XXXIV- SHARE OF COST ASSIGNED TO RED MT. AREA

Year	INDEXES Ironton	Crested Butte	Tennessee Pass	Shrine Pass	Total	Percent Ironton of Total	Cost - Grand-Junction Dist. Adj.*	Cost for Red Mt. Area*
1962	15.9	21.0	11.1	30.5	78.5	20.0	211	42
1963	8.7	8.8	8.7	16.5	42.8	20.3	154	31
1964	19.0	14.4	11.6	20.5	65.5	29.0	190	52
1965	18.8	30.6	20.0	31.4	100.8	18.7	226	43
1966	7.0	8.7	8.9	14.2	38.8	18.5	180	32
1967	9.1	7.0	9.6	24.3	50.0	18.1	207	37
1968	22.4	17.4	13.3	24.3	77.4	29.0	182	55

*$1000

Those adjustment weightings are detailed in Tables XXXI and XXXIII for the Durango and Grand Junction Districts.

d. Snow removal needs versus cost indices

The plot of snow removal needs indices against cost indices is shown in Figure 71 as a summation of indices for the two districts to indicate a total for the Red Mountain-Coalbank Hill area. The snow index at Ironton Park was increased 20% and the index at Spud Mountain snow course was decreased 20% before they were averaged. This makes the snow removal needs index approximately equal to inches of snow water equivalent at the average elevation in the area.

This shows that at a zero snow index, there is a standby cost which is about 45% of the maximum cost during the 1962-68 period and 55% of the average cost. Assuming an average snow pack, a 25% increase in snow pack would result in about a 15% increase in snow removal cost.

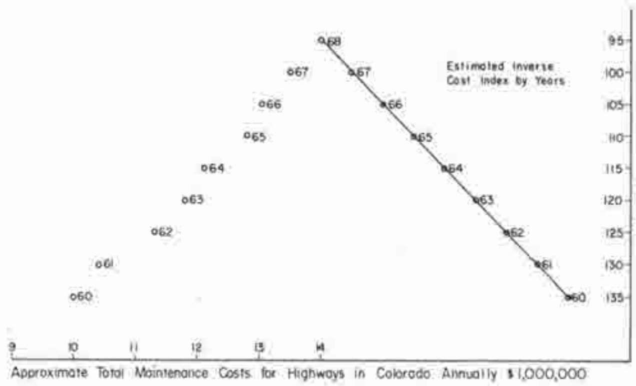

Figure 70. --Development of cost index by years.

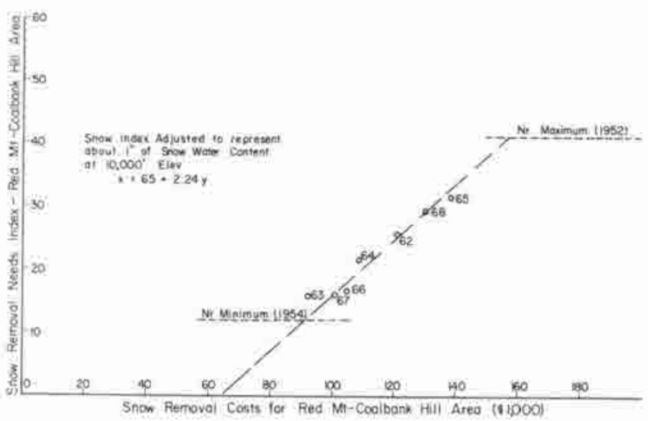

Figure 71. --Snow removal needs index versus costs (1967 level). Combined Grand Junction and Durango Districts.

e. Application of snow inconvenience indices to control of weather modification

Figures 73 and 74 show snow removal needs (inconvenience) indices for the years 1952 through 1968 based on total snowfall and snow water equivalent, respectively. The 1952 season had the highest snow removal needs index for any year since snow survey records were started in 1936. While this record would suggest that a year like 1952 would occur once in 33 years, other records indicate that snowfalls near this amount occurred at least twice in the period 1900 through 1935. It is also to be noted that the average exceeds the mean by about 25%, typical of weather data.

From a weather modification standpoint snow removal capabilities should be well within the range of normal planning to cover years when snow may reach average, 125% of average or perhaps 150% of average. Snowfall in excess of 150% of average may cause a significantly increased problem using normally available equipment and crews.

Figure 75 shows the relationship of seasonal snowfall (unadjusted) up to February 1 to that which occurred after February 1 up to April 15 for the years 1952 to 1968. While there is a slight indication of persistence in weather patterns, it is not adequate to predict what will happen in the way of subsequent snowfall. However, as shown in Figure 76, there is a fair correlation between snowfall which occurs up to February 1 and the total up to April 15. Figure 77 shows that there is little deviation in the snowfall pattern for the season after March 1. (This is in contrast to relationships between snowfall and runoff which must consider snowfall or lack thereof up through June).

The implication is that if snowfall is high in mid-winter, it is likely to be high as a total for the season. Conversely, if snowfall is light in mid-winter, it is highly unlikely that it will be excessive at the end of the season.

During the 1952-1968 period, the years 1952, 1957, 1958, and 1965 were critical. The differences in indices between snowfall and snow water equivalent in the years 1957 and 1958 was due to excessive snowfall between April 15 and May 1 in 1957.

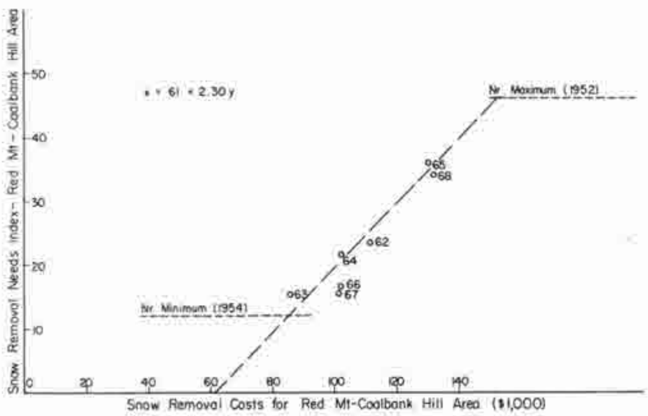

Figure 72. --Snow removal index versus cost (1967 level). Same as Figure 74 except cost level adjustment is reduced from 5% to 3% for each year from 1967.

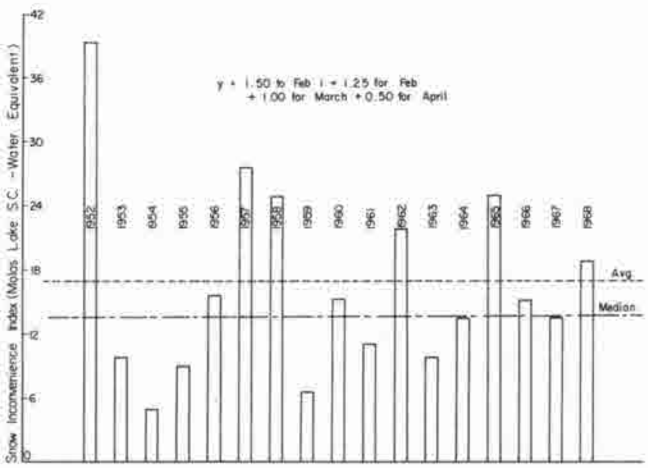

Figure 73. --Snow inconvenience index. Based on Molas Lake snow course water equivalent increase.

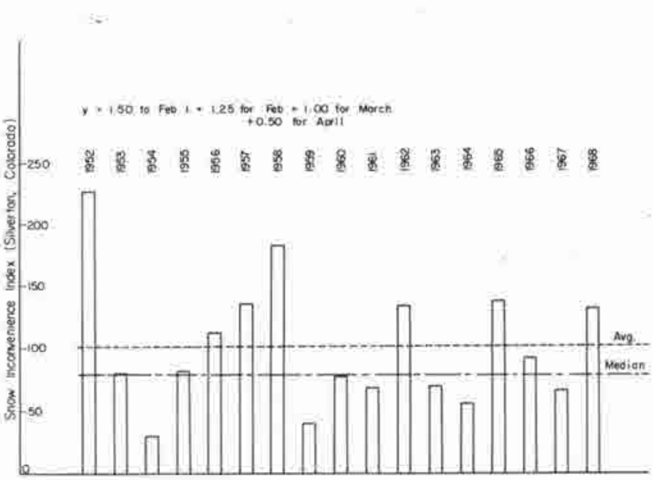

Figure 74. --Snow inconvenience index. Based on s snow depth on the ground (mean for period).

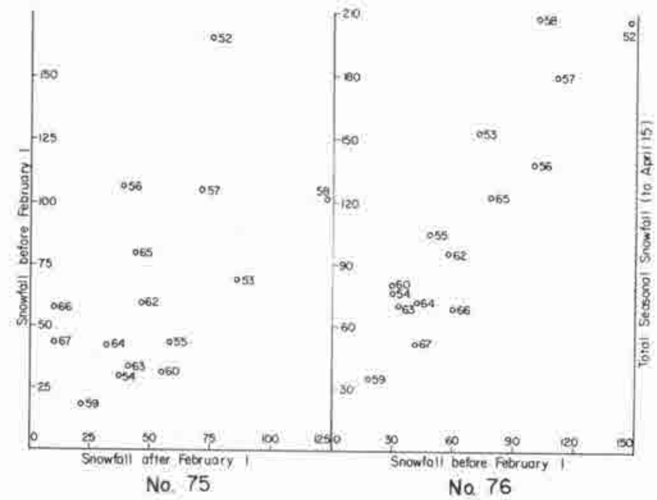

Figure 75. Snowfall at Silverton, cc = 0.40.

Figure 76. Snowfall at Silverton, cc = 0.80.

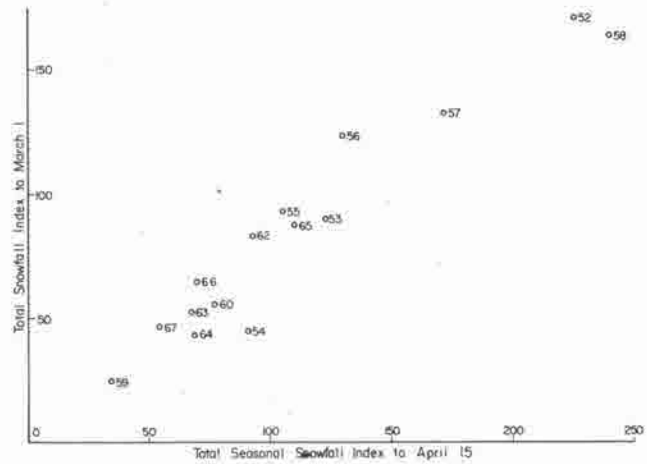

Figure 77. --Snowfall at Silverton, cc = 0.89.

I. Weather Modification Field Operations for the Pilot Project

The specific design for field operations of the Pilot Project must follow the resolution and finalization of the program design; i.e., the physical model, area selection, type of operations, hydrologic considerations, economics, etc. While the design studies for actual field operations are just getting underway, several approaches to be followed in some aspects of the program are apparent and have been considered in a general way.

1. Data collection

The field data to be collected fall into two general categories:

a. Data that will be used to assist in decision making for seeding operations
b. Data that will be needed in analysis and interpretation of program results

Data for use in implementing seeding operations will need to be available on a real-time basis and in a form that can be quickly interpreted and utilized. This will need to include information that can be used for immediate but preliminary evaluations of the operation for immediate feedback into the field operations. The data for more detailed analyses, however, can be quite usable even though it is not available until a later date when field recordings can be collected and analyzed. It is not expected that the immediate requirement for these results would justify the additional expense of real-time collection and analysis. This is particularly true since some of these analyses will have to use statistical procedures that in any case require a considerable accumulation of events before interpretations can be made with confidence.

The basic source of meteorological data for operations will be the National Weather Bureau Data Collection and Analysis System from which the data is made generally available through teletype circuits and the weather facsimile charts. For an area as small as the pilot project, these data will need to be supplemented considerably with both upper level and surface information. Much of the information needed in planning operations from the physical model presented in section V.A above will need to be obtained from local radiosondes in the immediate area. Upper data from one or two supplemental sites would probably be adequate for purely operational purposes. It is strongly recommended, however, that at least two stations be established, and preferably three. During the pilot phase of the operation, these supplemental stations can aid considerably in the evaluation efforts, particularly when making evaluations related to the physical model and the atmospheric water balance as discussed in section V.F above. One of these additional stations is needed downwind of the mountain massif.

The release intervals for upper air soundings are still under study. A number of advantages can accrue from a system of regular soundings supplemented by additional soundings that can best serve the program under existing conditions. Perhaps one of the best supplements to the regular sounding program can be the utilization of several continuously operating meteorological stations on isolated peaks. Such stations can be installed in essentially the free-air stream and at elevations in excess of 13,000 feet. Such stations are in or very near the crucial precipitation-formation altitudes and can continuously provide information on air temperatures, humidities, and changing wind directions.

Surface meteorological data should also be available. This can assist in interpreting changes in the general storm situations, low-level transport patterns of the seeding materials, and the distribution and characteristics of the precipitation that is occurring. To be of optimum value these data should be immediately telemetered to the operations control base.

Certain data necessary for evaluation, such as precipitation, streamflow, and surface meteorological data which are required for later analysis, might be more economically obtained, at least in the early stages o .he program, through the use of field recorders rather than immediate telemetry. Cost comparisons of the two systems will be made.

Various aspects of the data collection system have been discussed in documents transmitted to the Office of Atmospheric Water Resources and attached in Appendices I, IV, and V.

2. Seeding equipment and materials

The pilot model program for weather modification operations in the Colorado River Basin is being developed in a manner that will allow for the initiation of a pilot project in a specific sub-basin of the Colorado River Basin but will have the flexibility for expansion to other pilot projects in other portions of the Basin. This becomes an important consideration when evaluating the types of seeding and seeding equipment and materials to be utilized in an initial effort. The results of seeding presented in section V.B above strongly indicate that with cloud conditions of -20 and warmer, substantial increases in precipitation can be obtained using ground generators. Even greater increases might be obtained under some circumstances with the direct delivery of the seeding materials to the desired location within the cloud systems. It is the opinion of the authors that the effects of direct delivery of seeding materials has not been adequately tested under conditions that exist in the Colorado River Basin. The operational efficiency of a direct delivery system becomes an important aspect in its evaluation, since the efficiency of direct delivery by aircraft can be adversely affected by bad weather. In addition, direct delivery by either aircraft, rockets, balloons, etc., must still provide for the dilution of the seeding material concentrations from those at a point or line source to the values required in the seeding model. Field testing of the efficiency of direct delivery systems should receive further attention within the system of experimental programs being carried out by the Bureau of Reclamation. Since the ground delivery system has been tested in an experimental program with encouraging results and since the combination of both ground and direct delivery systems in the pilot project would considerably complicate analysis and interpretation, it is recommended that the initial pilot project in the San Juan Basin utilize only ground seeding. Seeding by direct delivery should receive primary consideration in a subsequent pilot project in the Colorado River Basin.

The primary criteria for selection of the seeding generators should be that they will deliver the concentrations of nuclei prescribed by the physical model for various meteorological situations. This, of course, involves considerations of the dispersion and transport of the seeding materials and their decay as well as the initial output of the seeding device. A CSU modified skyfire-type generator has been utilized in the experiments described in section V.B above. These generators have been laboratory tested and shown to provide a large number of effective nuclei at the range of temperatures to be encountered in wintertime field experiments in the Colorado River Basin. They have, in addition, been tested under field conditions in this Basin by the tracing of the materials to the target area sites and studies of their effects upon precipitation. These units are economical to produce (in the range $100 to $200) and simple to operate. They are not highly reliable operationally and do require considerable monitoring. The generator under development by the Bureau of Reclamation for utilization at remote sites has even superior output characteristics under laboratory conditions. It can be seen from efficiency curves for the respective units (Grant and Mielke, 1967; Atmospheric Simulation Lab., 1969) that the new generator produces about one-half as many effective nuclei at -12 but about three times as many effective crystals at -20. These comparisons are based upon laboratory tests only. They should also be made under field conditions. These new USBR units are considerably more expensive ($2,000 to $3,000 plus telemetry) than the needle-acetone generators but are believed to be suitable for use at remote sites in the field and should operate with considerably more reliability. Very preliminary considerations indicate that it would take around ten years to recover initial investment costs with this type of unit if it were used at a site where either it or the modified skyfire types were suitable.

While only the modified skyfire type generator and the seeding generator being developed by the Bureau of Reclamation have been considered in this report, other type generators could meet the project requirements and might have specific advantages. The laboratory and field tests of the modified skyfire type unit can serve as a minimum standard for seeding equipment to be used.

3. Targeting of Seeding Operations

The transport and diffusion characteristics of the seeding materials in the atmosphere is the least clearly defined aspect of the seeding model for the Colorado River Basin orographic clouds. The procedures to be recommended for use in the placement of seeding generators and operational decisions are being developed from:

a. Comparison of wind tunnel results with those obtained from prototype field measurements
b. Comparison of computer modeling results with field prototype measurements, and
c. Direct interpretations and analyses of field ice nuclei measurements and analyses of seeding results.

The complexities in considering the transport and dispersion of the seeding materials are apparent. Analyses in progress involving both the interpretation of field observation and of transport observed in the wind tunnel show through mixing of the seeding affluent in broad canyons leading into the high mountains. This can under some circumstances considerably facilitate the supply and mixing of the seeding materials that feed into the broad upper portions of these canyons. The questions of transport and dispersion of the seeding material will receive primary consideration in the design studies during the next few months. It is expected that most ground seeding activities can be carried out from accessible sites utilizing a combination of stationary and mobile seeding generators supplemented by a limited number of units installed at remote sites.

4. Program Control

The requirements for the control of the field program have been discussed in Section III above. It is expected that, at least in the early phases of the pilot program, field program control can be conducted most efficiently through the use of a field office, manned by experienced personnel and supported by access to computer services that provide real-time calculations of: natural precipitation possibilities, suitability for modification, expected streamflow response, cost-benefit interpretations, detailed operational procedures to employ, and real-time evaluations of efforts underway. It is probable that in the initial stages of the pilot project many of these analyses will have to be made with the aid of nomographs and charts with a phase-over to computer interpretations as the procedures are refined and the computer facilities become directly accessible.

VI. SUMMARY OF THE FIRST PHASE OF A PROGRAM TO FORMULATE A DESIGN FOR A PILOT PROGRAM OF WEATHER MODIFICATION OPERATIONS IN THE COLORADO RIVER BASIN (Summary of Interim Report, October, 1969)

A. Introduction and Objectives of Pilot Project

Operational systems to enhance precipitation in some areas by 1972 was set as a goal by the Assistant Secretary of Interior in the November 1966 Bureau of Reclamation Planning Document. The Colorado River Basin Act of 1968 specified further the Bureau of Reclamation's obligation to develop early means of water augmentation. The need for additional water supplies in the western United States is well known and continues to grow.

The 1966 Bureau of Reclamation Planning Document includes an operational adaptation sequence for accomplishing this objective. This sequence calls for a progression of efforts from experimental, to pilot, and finally, to fully "operational" projects. The term "operational" in this planning document refers to future projects to be initiated after a useful capability is achieved and would-be programs undertaken to obtain benefits of an applied technology. This report is a summary of contracted efforts by Colorado State University during the first year to prepare a specific design for pilot projects within the Colorado River Basin.

The pilot program of weather modification in the Colorado River Basin is intended to serve as a transition from experimental to fully applied programs. The detailed objectives of the pilot program being developed for the Colorado River Basin have been stated in a number of different ways. After many discussions, the prime objective of the pilot project was defined by the Bureau of Reclamation (Kahan, 1969) to be ". . . to provide a sound evaluation of precipitation increases from operational type cloud seeding over a large area." The design of the pilot project was originally scheduled over a three-year period. The findings presented in this report summarize the result of the first year's effort, and consequently, must be considered tentative.

The design efforts can be classified into four broad categories: The first is concerned with the basic design of the overall program. The second involves definition of operational opportunities. The third pertains to operational procedures to be employed, and the fourth includes control procedures for actual field activities.

B. Physical and Experimental Basis for a Pilot Model Program of Weather Modification in the Colorado River Basin

The physical basis for treating cold orographic clouds by seeding was presented by Bergeron (1949), and discussed in more detail by Ludlam (1955). The orographic-induced clouds along the windward portions of the mountain ranges over the western United States are frequently composed of supercooled liquid droplets. The temperature activation spectrum of natural nuclei is such that the number of effective natural nuclei may not meet cloud requirements for converting the cloud water to ice form at the warmer cloud temperatures and higher condensation rates. In such cases snow may not develop, or precipitation processes may be inefficient. If artificial nuclei can be activated in the saturated orographic airstream upwind of the mountain barrier, a more efficient conversion of cloud water to ice crystals should result in increased snowfall. Otherwise, the unconverted cloud water evaporates in the subsiding airstream to the lee of the mountain barrier.

A simple model presented by Grant et al, (1968), shows the variation of optimum ice nuclei concentrations as a function of vertical motion and cloud system temperatures. This model is based on an equating of the diffusional growth of ice in the cloud and the formation of condensate by topographic lifting. Preliminary results of the Climax, Colorado, weather modification experiment for the years 1960-1965 show that the distribution of seeding effects with cloud temperatures follow the trend indicated by the model.

Following a similar approach, a more refined model is derived by Chappell, et al, (1969), that is tailored for existing and estimated cloud conditions at Climax and Wolf Creek Pass, Colorado. This model is in agreement with the results from the randomized seeding experiments at Climax and Wolf Creek Pass and serve as the physical basis for the pilot project. The preliminary analysis of the Climax experimental data from 1960-65 was reported by Grant and Mielke (1967). The original sample of 283 randomized events indicated that the average precipitation was substantially greater on seeded days than on corresponding non-seeded days when cloud top temperatures were -20C and warmer. The average precipitation on seeded days was less than on non-seeded days when cloud top temperatures were -24C and colder. Little change in precipitation between the seeded and non-seeded days was noted for cloud top temperatures from -21C through -23C. This is in accordance with seeding effects inferred from the physical model. Further analyses of the 1960-65 Climax data is now completed and results from two other independent samples (Climax II [1965-68] and Wolf Creek I [1964-68] are available for comparison. Climax II can be considered as completely independent since this experiment was carried out subsequent to the determination of significant model stratifications and presented at the Fifth Berkeley Statistical Symposium in December 1965. Further analyses of Climax II and

Wolf Creek samples substantiate the initial findings of the Climax I sample. These analyses all show substantial increases in precipitation, generally in excess of 100%, when coldest cloud temperatures are in the range from -12C to -20C. The analyses also all indicate statistically significant decreases in precipitation for the seeded cases when cloud temperatures are as cold as -26C. When coldest cloud temperatures are in the range from -21C to -25C seeding effects are small and variable. These results are again in accordance with seeding effects inferred from the physical model. Other meteorological parameters vitally affecting the modification potential are considered and their importance delineated. The model not only serves to define operational opportunities, but also provides a basis for refining seeding techniques.

C. Pilot Project Area

The pilot project design studies are being concentrated on the San Juan Area of southwestern Colorado. This entire mountain massif is being considered. The physical model and experimental results suggest this area should be one of the most productive in the Colorado River Basin from the standpoint of augmenting water supplies from weather modification.

D. Pilot Project Evaluation

Optimal evaluation in terms of changes in precipitation should utilize unseeded periods randomly interspersed with seeded periods. Optimal evaluation in terms of streamflow, on the other hand, requires that operational seeding be carried out for all opportunities in order to maximize the total effort. Since emphasis for the pilot project will be evaluation, priority is being placed on precipitation data.

The utilization of the 24-hour sampling unit appears to be most satisfactory for precipitation evaluation. This unit is long enough to minimize contamination problems from a previous seeding period, yet short enough that adequately defined meteorological descriptions are possible. Based on these and other factors, the 24-hour period is receiving primary consideration.

Statistical tests that are being planned do not lose substantial power if the proportion of seeded to non-seeded events is varied slightly from 50-50. However, unless randomization is practiced within each meteorological category, a substantial departure from a 50-50 split could occur in the events of a small sub-set and substantially impede evaluation efforts. A split very close to 50-50 appears at this time to be the most conservative and desirable approach.

It is estimated that a full-scale operational seeding program in the San Juan area might produce increases of the order of 30% in total streamflow using presently available techniques. Historical annual streamflow correlations between the San Juan area and the Aspen area in central Colorado are .85 (Morel-Seytoux, 1968). If the Aspen area is used as a control, streamflow increases in the San Juan area of 30%, 18%, 15%, and 10%, would be detected at the 5% level with about 90% power in 2 years, 5 years, 7 years, and 15 years, respectively. If the randomization scheme during each year of operation includes seeding during 50% and 60% of the events, the change in streamflow should be detected at the 5% level with about 90% power in 7 and 5 years, respectively. This assumes the actual increase during the seeded interval is around 30%.

Analyses of the resulting precipitation data from the pilot project should employ the use of both parametric and non-parametric approaches. Appropriate parametric techniques should include simple regression analyses using gamma transformations and distribution and effect dependent optimal tests. Non-parametric tests such as the two-sample Wilcoxon and the sum-of-squared-ranks test should be utilized. Assuming differences in seeding results and scale changes, Duran and Mielke, 1968, have shown that the sum of squared ranks test has excellent large sample properties for a broad class of distributions which appear to closely approximate actual precipitation distributions. Multivariate techniques are being investigated to see if even more powerful robust techniques can be developed. Univariate and multivariate regression approaches should be applied to analyses of streamflow data resulting from the pilot project (Morel-Seytoux, 1968).

E. Operational Procedures

The specific design for field operational pilot project must follow the resolution and finalization of the project design; i.e., the physical model, area selection, type of operations, hydrological considerations, economics, etc. While the design studies for actual field operations are just getting underway, several approaches to be followed are apparent and have been considered in a general way. Data collection, seeding equipment, and operations control are primary considerations.

The field data to be collected fall into two general categories:

1. Data that will be used to assist in decision-making for seeding operations, and
2. Data that will be needed in analysis and interpretation of program results.

The basic source of meteorological data for operations will be the National Weather Bureau Data Collection and Analysis System. This data is available through teletype circuits and facsimile charts. For an area as small as the pilot project, these data will need to be supplemented with both upper air and surface meteorological information. It is being recommended that at least two, and preferably three, radiosonde stations be established in the area. These can be supplemented by two or three stations installed on selected mountain peaks that are essentially exposed to the free-airstream at elevations in excess of 13,000 feet. Such stations would be in or very near the crucial precipitation formation altitudes and can continuously provide information on air temperatures, humidities, and changing wind directions and speeds. Limited surface meteorological data can assist in interpreting changes in general storm situations, low-level seeding transport patterns, and the distribution of characteristics of precipitation that is occurring. Studies are underway to establish the number and types of observations necessary for the proper operation of the project without placing undue financial or operational burden resulting from an excessive observational network.

Analyses of randomized seeding at Climax and Wolf Creek strongly indicate that under the proper meteorological conditions substantial increases in precipitation can be obtained using ground generators. Even greater increases might be obtained under certain circumstances with direct delivery of the seeding material to the desired location within the cloud system. It is the opinion of the authors, however, that the effects of direct delivery of seeding materials has not been adequately explored and tested under conditions that exist in the Colorado River Basin. The operational efficiency of a direct delivery system is an important aspect of its evaluation since the efficiency of direct delivery by aircraft can be adversely affected by bad weather. In addition, direct delivery by either aircraft, rockets, or balloons must allow for proper dilution of the seeding material concentrations from the originating point or line source to the desired values within the cloud system as given by the seeding model. Field testing of the efficiency of direct delivery systems should receive further attention within the system of experimental programs being carried out by the Bureau of Reclamation. Since the ground delivery system has been tested in experimental programs with encouraging results, the combination of both ground and direct delivery systems in the pilot project would considerably complicate analysis interpretation, the initial pilot project in the San Juan Basin is being designed to utilize only ground seeding. Seeding by direct delivery should receive primary consideration in a subsequent pilot program in the Basin.

The primary criteria for selection of the seeding generators should be that they would deliver the concentrations of nuclei prescribed by the physical model for various meteorological situations. The CSU modified skytype generator has been both laboratory and field tested in the Climax and Wolf Creek experiments and shown to provide the large number of effective nuclei required for temperatures accompanying wintertime snowfall in the Colorado River Basin. Other type generators almost certainly have higher operational efficiency and are more adaptable to remote telemetry. The skyfire type generator can serve as a minimum standard for the seeding equipment to be used.

The transport and diffusion characteristics of seeding materials in the atmosphere is the least clearly defined aspect of the seeding model. The procedures to be recommended for use in the placement of seeding generators and making operational decisions are being developed from:

a. Comparison of wind tunnel results with those obtained from prototype field measurements
b. Comparison of computer modeling results with prototype measurements, and
c. Direct interpretations and analyses of field ice nuclei measurements and analyses of seeding results.

It is expected that most ground seeding activities can be carried out from accessible sites using a combintation of stationary and mobile seeding generators supplemented by a limited number of units installed at remote sites. It is believed that, at least in the early phases of the pilot program, field control can be conducted most efficiently through the use of a field office, manned by experienced personnel and supported by access to computer services that provide real-time calculations of: natural precipitation possibilities, suitability for modification, expected streamflow response, cost-benefit interpretations, detailed operational procedures to employ, and real-time evaluation of efforts underway. It is probable that in the initial stage of the pilot project many of these analyses will have to be made with the aid of nomograms and charts with a phase-over to computer interpretations as the procedures are refined and computer facilities become directly accessible.

F. Economic Considerations

The general research objectives of the design study are to

1. Explore, rank, and measure the economic consequences of weather modification, taking both benefits and costs into account
2. Evaluate economic attributes of alternate methods of weather modification in relation to probable variations inherent in various techniques.

Trade-off prices are being considered for options selected or rejected, that can more fully guide research policy and public action. The economics aspects can be categorized as

a. Direct impacts (water availability)
b. Social impacts (i. e., effect on human activities, recreation, etc.)
c. Private impacts (i. e., moisture for ranching in the area)
d. Non-economic impacts (i. e., transportation hazards)
e. Indirect impacts (i. e., the effects on forest production)
f. Quality impacts (i. e., the quality of the water)

Irrespective of the classification of a given impact it is necessary to rank the numerous consequences of modification by probable or possible levels of importance to the pilot project. A three-stage ranking of significance as primary, secondary, and tertiary is being considered for this purpose. The primary impacts being given emphasis in the pilot design study are:

1. A general definition of the economic value of the additional water resulting from modification systems,
2. Delineation of the more critical negative benefits of weather modification, and
3. Cost analyses systems to allow for future cost-effectiveness comparisons of alternative modification techniques, given various probabilities of program success.

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APPENDIX I

Field Program (Suggested) 1968-69 Winter Season for Pilot Program of Weather Modification Operations Colorado River Basin

August, 1968

INTRODUCTION

The program to design a specific pilot project for the Colorado River Basin was initiated in April, 1968. A work plan for developing the design has been completed and reviewed with consultants. Work on the various phases is underway. However, several vital areas are in an early stage of development. A field program for the 1968-69 winter season is outlined in this report. This field program has been developed to facilitate the overall design of the pilot program and to expedite the time when the pilot program can be operated at a high level of efficiency. The short time remaining before the winter season begins and the limited funds that the Bureau considers might be available have been a key consideration in the development of these plans.

OBJECTIVES

The limited field program for the 1968-69 winter season should have the following objectives: (1) reconnoiter the feasibility of using specific observational and operational sites, (2) test certain equipment and field procedures, and (3) fill in a few important gaps in hydrometeorological data for specific areas.

SELECTION OF AREA FOR PILOT PROJECT

Emphasis in the early stages of the design program have been concentrated on the selection of sub-areas in the Colorado Basin that appear to be the most satisfactory for initiation of pilot operational programs. Commercial programs of weather modification operations have in general been conducted for individual watersheds. Moderate- or large-scale weather modification operations for the Colorado River Basin will, from the nature of seeding activities, affect a number of sub-basins. Consequently, the definition of the subdivisions of the Colorado River Basin are being prepared for mountain massives that would essentially be the targets for weather modification efforts. These mountain massives form the headwaters for a number of individual watersheds. The seven sub-areas into which the Colorado River Basin is being divided will be discussed in more detail in subsequent reports.

The design being developed has the capability for determining the incremental increases in water supplied from the weather modification efforts. At least two target areas, each with appropriate control regions, will initially be needed. While it will be necessary to instrument each of these two areas from the start for observational purposes, the seeding operations for the first seeded year will be carried out for a single pilot area selected on a random basis. The area to be seeded can be operated without interruption during any individual winter season in an optimal manner using contemporary technology. The operations in a given area will not be suppressed as a consequence of the randomization.

The following two areas appear to be most satisfactory for a pilot program of weather modification operation in the Colorado River Basin:

1. The San Juan Mountains. This includes drainage areas from Lake Fork to the New Mexico border.
2. The Upper Basin of the Colorado River. This includes drainage basins from Williams Fork to Troublesome Creek.

The recommendation of these two areas is based upon the following considerations:

1. Both basins make a substantial contribution to the flow of water in the Colorado River Basin. This is true in terms of either water supplied per unit area or of total flow.
2. It is highly desirable that sub-areas of the Colorado River Basin near the eastern extremity of the Basin serve as initial pilot projects. This will maximize the upwind areas in the Colorado River Basin where experimental programs that can be carried out to further technological progress without the hinderance of massive seeding. This becomes extremely important when one considers that within 10 to 15 years, weather modification operations will probably be routinely carried out for large portions of this and other basins. Subsequently, the ability to explore and learn in a natural environment may cease to exist. Such a development of operational programs from east to west across the Colorado River Basin would maximize the interval of time available for the continued development of seeding technology under uncontaminated conditions in at least some sections of the Basin.
3. Substantial special operational facilities, in addition to regular ESSA, USGS, SCS,

etc. facilities, are available in support of the design efforts and the future operational program in these areas. The Upper Basin of the Colorado River includes streamflow and precipitation data taken for a number of years at the Fraser Experimental Forest. They include high elevation precipitation and weather data from the Berthoud Pass-Mine's Peak area which is available from the Forest Service Avalanche Research Station. They also include the precipitation profile data available for Berthoud Pass from Colorado State University. In the case of the San Juans, four years of precipitation data over Wolf Creek Pass are available through the Atmospheric Science Group at Colorado State University.

4. The use of these two specific orographic barriers would provide a test of cloud seeding operations under extreme conditions in the orientation of the topography. A large section of the San Juan Range, for example, can frequently be nearly parallel to the airflow during important storms. The Upper Basin, in contrast, is primarily perpendicular to airflow during major storms. Weather modification models being developed at Colorado State University* indicate that the method of operations and the results from weather modification operations should be highly variable as a function of the topographic profile and topographic orientation.
5. As weather modification becomes a major endeavor, water rights conflicts in the immediate vicinity and at more distant locations could develop. These two areas could serve very adequately to test a wide variety of such problems.
6. Pilot operational programs in these two areas could also have important beneficial effects on watersheds outside the Colorado River Basin. In the case of the San Juans, this would effect the Rio Grande Basin, an area consistently in need of increased water supplies. In the case of the Upper Basin of the Colorado River, the South Platte and North Platte Basins could also be affected. In the case of the South Platte, the transdiversion in the Big Thompson system would have a additional value. These possibilities of beneficial effects downwind of the Colorado River Basin could adequately be tested by the use of these two specific areas.
7. In the case of the Upper Basin of the Colorado River, the complications introduced from access restrictions to the wilderness areas is minimized in comparison to some other areas.
8. The two areas proposed are large enough to properly permit determinations of atmospheric water balances. These determinations hold promise in providing a very important method of monitoring Basin water supplies.

It is believed the Park Range would make an excellent control area or reference for the Upper Basin of the Colorado River. This recommendation is based on the following considerations:

a. The Park Range is immediately upwind and would not be contaminated by seeding for the Upper Basin.
b. The north-south orientation of the main barrier is very similar to that of the Upper Basin area.
c. The latitude of the Park Range is almost equivalent to that of the Upper Basin.
d. The upstream terrain resembles that of the Upper Basin so that precipitation episodes should react similarly to various storm conditions.
e. Sufficient instrumentation is already available in the Park Range for serving as a control area.
f. The area should serve as a good control area for both statistical and physical studies when compared with the Upper Basin.
g. The similar latitudinal and topographical features of the Park Range, combined with its close proximity to the Upper Basin, make it an ideal location for Coop studies embodying simultaneous comparisons of non-seeded and massive seeded storm conditions.
h. The Park Range area would still be available as a testing area for new operational techniques and new equipment certain to evolve in the near future.

FIELD TASKS

The accomplishment of all or part (hopefully all) of the reconnaissance programs listed below would assist in the detailed planning of the pilot program. Their successful accomplshment would go a long way in assuring efficient operations for an actual pilot program from the time of its initiation. In starting any field program of weather modification operations, everyday problems of accessibility, communications, data collection procedures, and equipment can adversely affect the program. In many programs it is necessary to use the first year as a shakedown period. It is believed that the successful completion of the tasks below would make it possible for a pilot project for the areas specified to be operated from its inception at a reasonably high level of efficiency.

The field tasks suggested are divided into five categories. These are individual categories that can be treated independently or, of course, can

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*L. O. Grant, C. F. Chappell, and P. W. Mielke, Jr., 1968: The recognition of cloud seeding opportunity. Paper published in the Proceedings of the First National Conference on Weather Modification, Albany, New York, April 28-May 1.

be undertaken in a combined effort. They are presented independently to facilitate planning, budgeting, and contracting efforts.

Task No. 1: Transportation and communication reconnaissance.

A reconnaissance of the accessibility of operational and observational sites should be carried out under both winter and summer season conditions. Site studies are being explored from available maps and published information. Only local reconnaissance, however, can specifically consider and rate the comparative accessibility and quality of potential sites.

Present design plans for the pilot program place emphasis on the unit cost of added water from weather modification operations. An adequate quantity of good quality data will be required to efficiently operate and evaluate the pilot program. Observational data programmed for the pilot program are to be directed toward this end. The inclusion of substantial quantitites of supplemental data that might be useful or desirable but not essential will be avoided. Appendix IA shows a listing of potential sites being considered for the installation of additional stream and precipitation gaging stations. These potential sites should be surveyed and evaluated by qualified engineers. The evaluation should include considerations of accessibility during all seasons.

The accessibility and communication reconnaissance should be extended into the respective watersheds to locate at least three sites, if possible, that would be suitable for the installation of telemetered precipitation gages. This applies to both watersheds requiring supplemental streamgaging and those already having adequate streamgaging facilities. Sites at low, intermediate, and high elevations above the streamgaging should be considered. When this is possible, the sites should not only be rated, but objective estimates of the effort and expense required to install and service each site should be made.

A uniform treeline to the windward at an angle of approximately 30 degrees has been found to be characteristic of the best snowfall observation sites* in the Central Colorado Rockies area near Climax. Angles of uniform vegetative shielding to as low as 15° to 20° have given good results. Vegetative cover to over 45° have consistently resulted in questionable data. Non-uniform cover, such as is provided by a few isolated trees has given erratic results--sometimes satisfactory and other times very poor. The vegetative cover downwind of the site (except in the immediate vicinity) does not critically affect the site. This means that the critical directions for canopy shielding in the Colorado Rockies is generally from south through west to north, and even less restrictive than this depending on the specific area and location. Shielding from the southwest is probably more crucial on the south slope of the San Juans while shielding from the northwest is probably more crucial on the northern slopes of the San Juans and in portions of the Upper Basin of the Colorado River.

Appendix IB shows a list of potential areas for the installation of ground generator sites. They should be surveyed and evaluated also. For sites listed in the appendix, remote units would probably be required, but access during the winter would still be necessary for repair and providing emergency supplies. Again, as in the case of the stream and precipitation gaging stations, the suitability of the respective sites for telemetering the data should be evaluated.

It is suggested that field survey personnel carry surveying altimeters and thermometers for recording vital data at all sites being evaluated. A tape recorder or specific forms would help in assuring data completeness.

The Bureau of Reclamation should consider seriously the alternatives of their subcontractor owning or using Bureau of Reclamation equipment for the transportation equipment (four-wheel drive vehicles and snowcats that will be necessary for the accomplishment of this task).

The SCS out of Portland, Oregon, has facilities and teams available for evaluating sites with respect to their suitability for telemetered observations.

Detailed descriptive logs should be kept for trips into the respective areas. These should describe accessible routes and, in particular, bad spots which could cause serious troubles in subsequent seasons. The notes should be made in sufficient detail so that corrective measures might be taken in certain spots during the following summer season.

It is recommended that the respective sites be explored during the fall season and that the access routes be marked prior to December. Serious evaluation of the sites should be made during at least two visits to the respective sites between February 1 and April 15 when snow problems are worst.

The communication reconnaissance for both the stream and precipitation gages should be concerned only with communication aspects and not with the complete instrument package.

Task No. 2: Upper air reconnaissance.

The reconnaissance of sites for upper-air sounding stations and the collection of some data would facilitate future planning.

It appears probable that supplementary upper-air sounding stations will be the most practical and economic means of obtaining input data for operational weather modification programs in

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*Charles F. Leaf, 1962: Snow measurement in mountainous regions. Master's Thesis, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado, February.

sub-areas of the Colorado River Basin. This supposition can be tested by the operation of supplemental units in the specific areas of concern. Most information could be obtained with one portable unit, although two units operating simultaneously would have many advantages. In any case, an upper-air sounding station should be mobile and should run tests from a series of sites around the proposed pilot areas. The tests from the respective sites should have the following three objectives:

1. Evaluation of the site as a practical base for future stations
2. Determination of the representativeness of the site for making airflow measurements that are important in determining drift patterns for ground-released seeding materials
3. Determination of the representativeness of the site for providing information for seeding models and atmospheric water balance determinations. Priority should be given to the sites listed below in the following order:

   a. The Durango-Ignacio area
   b. Dove Creek area
   c. Montrose area
   d. Del Norte area

   For the Upper Basin of the Colorado River, the following sites should be explored with preference in the order listed:

   a. Kremmling area
   b. Granby area
   c. Loveland-Longmont area

Task No. 3: Equipment comparison.

A few well-located, reliable precipitation stations will be of vital importance to the pilot project in planning operational activities, in accessing results both during storm and in post-operational analyses, and in determining the economic value of the activities. The immediate requirement for data for operational purposes necessitates that at least a portion of these data be immediately available through a telemetry system. It is not obvious that any current snowfall-measuring and telemetry system is superior. It is apparent that they all have certain deficiencies. It is strongly recommended that an equipment comparison program be established for this coming winter to evaluate the limits of the respective systems under conditions that will be actually experienced in the proposed pilot areas. It is assumed that one equipment comparison testing program in the general area of the Colorado Rockies would be adequate. It would be preferable if such a comparative effort could be made in both the northern parts of the Colorado River Basin and in the San Juan area since the snowfall characteristics are different in the two areas.

It would be highly desirable if this comparison could include a test of the total system (i.e., the precipitation gage and the associated telemetry system). It is unlikely that this will be possible in all cases during the coming winter. The following are items for consideration in setting up this program:

1. Site selection should be given careful consideration. In addition, allowance should be made to have adequate room available for the various units to be tested.
2. At least two shielded weighing gage units and at least three snowboards that can be read manually each day should be interdispersed in the test plot. This will provide a reference from the intercomparison of these units between both themselves and the telemetered data.
3. This testing program should be under the overall supervision of a disinterested government agency or university group.
4. Our group would like to participate in the selection of the specific site or sites and the layout of equipment once the general area is selected. Experts from the Forest Service and/or the SCS should also participate in this site determination and equipment layout.
5. Systems that should be considered might include:

   a. Weighing gage
   b. Tipping bucket
   c. Electrical capacitance
   d. Radioactive probe
   e. Light sensor
   f. Snow photography
   g. Snow pillow
   h. Etc.

Task No. 4: Collection of basic data

The tasks described above, with the exception of a portion of that described in the upper air reconnaissance, have dealt with data collection and equipment but not the actual collection of data for use in climatological and meteorological studies of the areas. No extensive data collection program, aside from those already in progress, is recommended for this winter. However, a limited data collection program could prove very useful.

1. Precipitation data
   Reasonably detailed information of the precipitation profile with elevation in the Upper Basin of the Colorado River is available from historical data collected by the Forest Service, the Berthoud Pass profiles operated during the past four years by CSU, and from reference from the profiles obtained by the Bureau of Reclamation at Rabbit Ears Pass. In the case of the San Juans, limited data on the vertical profile precipitation by storms is available from the CSU profiles over Wolf Creek Pass. It would be helpful to supplement the Wolf Creek profile with about three additional stations and to obtain a north-south profile over the east-west portion of the San Juan area. This could be done by installing a

network of gages to be read daily over this range from Durango to Ridgeway. As an alternate, it could also be accomplished by running a profile from around Stoner, through Rico over Lizard Head Pass to around Placerville. This network could be installed along the highway with gages at intervals of about 2 miles far enough back from the highway to avoid any effects of snow plows. It would be desirable to install a couple recording gages on each side of the pass. During such a reconnaissance study an inexpensive manually-read system would be satisfactory. Eight-inch shielded gages on a stem providing for alternating height as the snow depth increases is recommended. Snowboards could also be placed at each site for comparative measurements of snow depth and water content each day. Also, for establishing background levels, samples of new snow for silver analysis should be taken.

2. Streamflow data
   Should it be feasible to establish that some of the recommended streamgage sites are satisfactory, the installation of gages at these sites would make possible the collection of additional streamflow data during during the coming water year. This would be most useful in planning the programs for these areas and starting the establishment of records prior to the initiation of the actual seeding activities.
3. Ice nuclei
   The collection of even a limited amount of background ice nuclei data to the southwest and west of the San Juan Mountains would be very desirable. It is recommended that the Schaefer mixing chamber or Bigg-Warner expansion chamber be used in the collection of the data. Since it is for reference purposes only, the discontinuity of observations will not be serious. While the acoustical unit would be quite adequate for plume tracking, etc., it is not believed that it would be adequate for establishing a background reference. Equipment specification can be supplied from our group if desired. An installation at Fort Lewis College in Durango might be advantageous.

   In the case of the Upper Basin of the Colorado River, Climax, Park Range, and Elk Mountain data should provide adequate reference.
4. Temperature profile
   Better definition of the cold air pooling in Upper Basin of the Colorado River would be of extreme value. A few temperature stations at different elevations from Kremmling along Highway 40 to Rabbit Ears Pass and between Fraser and Berthoud Pass would be most helpful. Temperature data taken from the Winter Park ski tow for all times of day and weather situations would provide excellent data.

<u>Task No. 5: Cooperative program--Coop 4</u>

Very useful information could be obtained by a cooperative effort of subcontractors of the Bureau of Reclamation in the Upper Basin of the Colorado River. This would provide personnel and equipment that would allow a coordinated look at certain aspects of the weather modification in these areas. Such a program could be planned for two or three short but coordinated studies for individual storms during a rather extended period of time, say February 1 through March 15. An alerting and notification system could be arranged so that the concentrated effort would be made only when significant storms are developing. Important problems that could be considered by such a cooperative effort might include:

1. Plume tracing for the specific pilot areas
2. Obtaining information on the physical processes of snow formation as determined from ice nuclei by parallel observations of ice nuclei, snow crystals, and radar observations of snowfall.

I. San Juan Sub-area

A. Reconnaissance for Stream Gage Sites

Site 1: West Fork of the San Juan River
Proposed site is located approximately 2 miles northwest on west Fork Campground Road from its intersection with Highway 160. Approximate elevation is 8000 to 8200 feet. Site to be located just outside of San Juan Primitive area.

Site 2: West Fork of Wolf Creek
Proposed site is located where Highway 160 crosses over West Fork of Wolf Creek near west end of Wolf Creek Pass. Elevation is approximately 8200 feet.

Site 3: Piedra Watershed
Proposed site is located on Piedra River between the junctions of Huerto Creek and Middle Fork near the vicinity of the Bridge Ranger Station; approximate elevation is 7800 feet.

Site 4: Piedra Watershed (Little Sand and Weminuche Creeks)
Proposed site is located just upstream from the junction of the Little Sand and Weminuche Creeks with the Piedra River or about 2 miles southwest on trail from the Bridge Ranger Station. Elevation is about 7600 feet.

Site 5: Dolores Watershed
Proposed site is located on Dolores River just south or downstream of Barlow Creek Inflow near the town of Coke Ovens. Elevation is approximately 9000 feet.

Site 6: San Miguel Watershed
Proposed site is located on San Migual River between the junction of Bear Creek and the town of Pandora. Elevation is approximately 8800 feet.

Site 7: Animas Watershed (Cement Creek)
Proposed site is about 2 to 3 miles north of of Silverton on Highway 353 where highway crosses Cement Creek. Elevation is approximately 9700 to 10,100 feet.

Site 8: Uncompahgre Watershed
Proposed site is on Uncompahgre River about 1 mile north of Ouray or just downstream of the junction of Canyon Creek. Elevation is approximately 7700 feet. There has been a gage near here previously.

Site 9: Gunnison Watershed
Proposed site is located on Lake Fork of Gunnison River just east or downstream from the intersection of the trail leading south to the town of Carson. This is about 5 miles upstream of Lake San Cristobal on Road 351 south of Lake City. Elevation is approximately 9500 feet.

Site 10: Gunnison Watershed
Proposed site is located on Lake Fork of Gunnison River at town of Sherman or just upstream from the junction of Cottonwood Creek. This is about 3 miles west of Site 8 on road 351. Elevation is approximately 9900-10,000 feet.

B. Reconnaissance for Precipitation Gage Stations

1. In association with proposed streamgages

Site 1: West Fork of the San Juan River
Access to high elevations of this watershed are restricted by the San Juan Primitive area. Just across the Continental Divide the high elevations of Goose Creek are out of Primitive area and may be accessible.

a. Probe 1: Up West Fork of San Juan River from proposed streamgage site to edge of primitive area vicinity of Barns Lake. Elevation about 8400 feet. One low elevation precipitation station desired.
b. Probe 2: South of Wagon Wheel Gap on road to Goose Creek Watershed. Up Goose Creek to near South River Peak. Two precipitation stations between 10,200 feet and 12,000 feet are desired in this watershed.

Site 2: West Fork of Wolf Creek
This watershed parallels Highway 160 along the west side of Wolf Creek Pass.

a. Probe 1: Along Highway 160 on west side of Wolf Creek Pass 3 precipitation stations are desired between 8500 feet and the summit of the pass (10,850 feet).

Site 3: Piedra Watershed
Access to high elevations of this watershed are again severely restricted by the San Juan Primitive area. Pagosa Creek headwaters reach the highest elevations before entering Primitive area.

a. Probe 1: Up Pagosa Creek watershed from Bridge Ranger Station. Desired stations are at about 8500 feet, 9400 feet and between 10,000 feet and 11,000 feet.

Site 4: Piedra Watershed (Little Sand and Weminuche Creeks)
Elevations over 11,000 feet in this watershed lie outside the San Juan Primitive area.

a. Probe 1: From Bridge Ranger Station 1 mile southwest along trail to junction of Little Sand and

Weminuche Creeks with Piedra River. Up Little Sand Creek Watershed to primitive area. Desired stations are a at about 8500 feet, 9500 feet, and be between 10,000 and 11,200 feet.

b. Probe 2: Take Huerto Creek road north from Bridge Ranger Station. At intersection of roads about 5 miles north of Ranger Station take left hand road to edge of Primitive area. Desired stations are at about 8,000 feet, 9000 feet, and 9600 feet.

Site 5: Dolores Watershed

a. Probe 1: Turn southeast off Highway 145 at Coke Ovens up Barlow Creek Trail up to near Dolores-San Juan Co. line. Desired stations are at 9800 feet, 10,600 feet and 11,200 feet.

b. Probe 2: Turn southeast off Highway 145 at junction of Dolores River Trail or about 2 miles northeast of Coke Ovens. Probe up headwaters of Dolores River to Dolores-San Juan Co. line. Desired stations are at 9800 feet, 10,600 feet and 11,200 feet.

Site 6: San Miguel Watershed

a. Probe 1: Take road east of Telluride up to Power Plant and continue on south toward Blue Lake as far as possible. Desired stations are at 9200 feet, 10,900 feet (at Power Plant), and between 11,800 and 12,300 feet.

Site 7: Animas Watershed (Cement Creek)

a. Probe 1: Go north of Silverton on Highway Highway 353 to town of Gladstone. Probe watershed northeast of Gladstone as far as possible. Stations desired are 9700 feet (Gladstone), 10,700 feet and between 12,000 and 12,800 feet.

b. Probe 2: Same as Probe 1 except probe along trail southeast of Gladstone as far as possible. Stations desired are 9700 feet (Gladstone), 10,700 feet, and between 12,000 feet and 12,600 feet.

Site 8: Uncompahgre Watershed

a. Probe 1: Stations are desired along Highway 550 vicinity of the summit of Red Mountain Pass (11,020 feet) and at 10,000 feet between towns of Guston and Ironton.

b. Probe 2: Go southwest of Ouray on Highway 361 up Canyon Creek to edge of Uncompahgre Primitive area. Desired stations are along Highway 361 at 8800 feet, 10,000 feet and at town of Campbird (10,500 feet).

c. Probe 3: Take Highway 110 northeastward from Silverton up the Animas River to town of Animas Forks. Go north on trail to edge of Uncompahgre Primitive area. Stations desired are at 10,000 feet Animas Forks (11,300 feet) and about 12,000 feet.

Site 9: Gunnison Watershed (Lake Fork)
Go south of Lake City on Road 351 past Lake San Cristobal to the intersection of the trail south to the town of Carson.

a. Probe 1: Go south on trail to Carson as far as possible. Desired stations are at 10,000 feet, 11,000 feet, and about 12,000 feet (at Carson).

b. Probe 2: Continue westward on Road 351 from intersection of trail to Carson to the top of Cinnamon Pass if possible. Desired stations are at 10,000 feet (town of Sherman), 11,000 feet and near top of Cinnamon Pass (12,450).

Site 10: Gunnison Watershed (Lake Fork)
No probe needed as Probe 2 for Site 9 will suffice.

2. In association with existing streamgages

Existing Site 1: San Juan River (East Fork)
There are two existing gages. About 7 miles north of Pagosa Springs turn east off of Highway 160 along East Fork of San Juan River.

a. Probe 1: Go up East Fork of San Juan River to junction with Quartz Creek. Travel up Quartz Creek as far as possible toward Quartz Lake. Desired stations are at 8300 feet, 9300 feet and between 10,000 feet and 12,000 feet.

Existing Site 2: Rio Blanco River
There is one existing gage. About 3 miles north of Blanco on Highway 84 turn east on Road 364 toward Blanco Basin School.

a. Probe 1: Go to end of Road 364 and continue up Rio Blanco to junction of north and east branches forming its headwaters. Take eastern branch as far as possible. Stations desired at 8200 feet (end of Road 364), 9000 feet (junction of northern and eastern branches forming headwaters), and between 10,000 feet and 11,800 feet.

b. Probe 2: Turn off Road 364 onto Fish Creek Road. Probe trail up Fish Creek to east of Flattop Mountain. Stations desired at 9000 feet and above 10,000 feet.

Existing Site 3: Vallecito Watershed
There is an existing streamgage on Vallecito Creek above Vallecito Reservoir. The higher elevations of this watershed are in the San Juan Primitive Area.

a. Probe 1: Probe up trail beginning at northeast end of Vallecito Reservoir to edge of primitive area if possible. Stations desired at 9000 feet and above 10,000 feet.

b. Probe 2: Probe up trail going north from the tourist camp on the east side of East Mountain to edge of Primitive area. Stations desired at 9000 feet, 10,000 feet and between 11,000 and 11,400 feet.

c. Probe 3: Go up road along Florida River to about 6 miles north of Upper Florida School. Turn right or east on Forest Service road toward top of Endlick Mesa. Stations desired at 8450 feet (intersection of Forest Service Road), 10,000 feet and between 10,800 feet and 11,500 feet (near or on top of Mesa).

Existing Site 4: Animas River

There is an existing streamgage on the Animas River at Howardsville. No probe needed as Probe 3 for Site 8 will suffice.

II. Upper Basin of Colorado River

A. Reconnaissance for Streamgages Sites

Site 1: Cascade Creek

Proposed site is located on Cascade Creek just upstream of its junction with South Fork about 1 to 2 miles east of Monarch Lake. Elevation is about 9000 feet.

Site 2: East Inlet of Grand Lake

Proposed site is located on the East Inlet of Grand Lake between Grand Lake and the Paradise Creek junction. Elevation is about 9000 feet.

Site 3: Ranch Creek

Proposed site is located on Ranch Creek just downstream of the junction of its northeast and southeast headwater branches, or about 1 to 2 miles east of the Girl Scout Camp. Elevation is about 9000 feet.

NOTE: All references to the Upper Basin of the Colorado River probably should read "Upper Basin of the Colorado River above Kremmling."

I. Reconnaissance for Generator Sites

A. San Juan

Site 1: Blue Mountain (about 8800 feet)
Site is located between Rito Blanco and Rio Blanco Watersheds about $1\frac{1}{2}$ miles south of Road 364 between its intersection with Highway 84 and the Blanco Basin School.

Site 2: Unnamed Mesa West-Northwest of Chromo (about 8500 feet)
Site is located between Highway 84 and Road 366 about 3 miles northwest of Chromo.

Site 3: Chris Mountain (about 8800 feet)
Site is about $1\frac{1}{2}$ miles southwest of the Turkey Springs Ranger Station or 5 miles north of Dyke.

Site 4: Haystack Mountain (7600 feet)
Site is 1 mile north of Highway 160 about 3 miles west of Dyke.

Site 5: Cade Mountain (9200 feet)
Site is about 10 miles north northwest of Pagosa Springs just west of the road and trail leading up McCabe Creek.

Site 6: Unnamed Mountain (8769 feet)
Site is just east of LaPlata-Archuleta County line abou 2 to 3 miles south of Highway 160. Trail is indicated from Highway 160 to top of mountain.

Site 7: Unnamed Mesa (8100 feet)
Site is about 3 to 4 miles east of Durango.

Site 8: Northern End of Menefee Mountains
Site is about 1 mile south of Highway 160 and about 5 miles east of Mancos. Radio tower is indicated at the proposed site.

Site 9: Campsite (8400 feet)
Site is about 10 miles north of Mancos and about 1 mile south of Turkey Creek. Take Road 184 north out of Mancos to near Moose Reservoir and then Forest Service road to Campsite.

Site 10: Ranger Station and Ranch (8100 feet)
Site is in Beaver Creek Watershed and about 10 miles northwest of Stoner. Access is on road north out of Dolores.

Site 11: Lodge (7950 feet)
Continue on north from Site 10 and survey possible generator site in vicinity of the Sawmill and Lodge near Woods Lake.

Site 12: Near Gurley Reservoir (8500 feet)
Site is on road going south from Highway 145 to Gurley and Cone Reservoirs. Survey for site between 2 miles northwest of Gurley Reservoir (highest ground) and Cone Reservoir.

Site 13: Unnamed Flat Mesa (9000 feet)
Site is on road leading north off of Highway 62 at Gutshall Gulch or about 5 miles north on Highway 62 from its junction with Highway 145. Sight is on flat mesa about 6 miles north of Highway 62 near the Montrose-San Miguel County line.

Site 14: Log Hill Mesa (8200 feet)
Site is on road going southwest from the town of Uncompahgre at the government spring.

Site 15: Pine Creek Mesa (8700 feet)
Site is on Rone Creek Mesa near ranch. Road leads south from Highway 6 about 3 miles west of Sapinero to the ranch a distance of about 5 miles.

Site 16: Dry Cedar Creek Road (7400 feet)
Site is on high ground about 2 to 3 miles south of Highway 6 on road leading into the Dry Cedar Creek. The road intersects Highway 6 about 10 miles east of Montrose.

B. Upper Colorado Sub-Area

Site 1: Gore Pass
Site located on Highway 84 in the vicinity of the summit of Gore Pass.

Site 2: McMahon Reservoir
Survey for possible sites along road going northwest and north from Highway 84 near Hinman Reservoir. Probe road as far as possible.

Site 3: Williams Fork Mountains
Sites desired above 9500 feet vicinity of Haystack Mountain and Beacon and on southeastward along ridge line if possible.

Site 4: Ute Pass
Site desired on or near summit of Ute Pass.

Site 5: Cottonwood Pass
Site desired on or near summit of Cottonwood Pass.

Site 6: North Willow Creek Reservoir
Probe road going north from Willow Creek Reservoir to Apatian Mountain for site above 8800 feet.

February 14, 1969

Mr. Pat Hurley
Office of Atmospheric Water Resources
U.S. Bureau of Reclamation
Denver Federal Center, Bldg. 67
Denver, Colorado 80225

Dear Pat:

The system of randomization for the pilot project remains unresolved following the discussions at the Bureau meeting last Tuesday. This is a vital point that must be resolved before many other aspects of the planning can go forward. Aside from our general planning, it will be an important factor in the contractual arrangements that you will be making for the field operations. The following are a few comments that relate to this point. A few comments on accretion and targeting are also included. I would like to get together with you, Archie, and others in your office shortly after I return from California next week so we can immediately set the wheels in motion to see what steps should be taken to reach a decision on the randomization system.

The basic nature of the pilot project needs to be clarified before the randomization scheme can be set. If the program is to be a pilot model of a research or experimental program, then the annual randomization should not be used. Clearly a much shorter interval (probably 24-hour periods) would allow cleaner statistical analyses. In our design efforts to date we have assumed that the pilot program is to be a pilot model of an operational [applied] program. If this is the case, the primary considerations should be operational rather than statistical. On-and-off operations do not represent an operational simulation. The concept of a randomized block as suggested by Braham is an alternative that is already incorporated. The block being used, however, is the natural period of a winter season, rather than a subdivision of a season. A fully operational program of seeding the Colorado River Basin will relate to the natural period of a snow accumulation season and not the shorter on-and-off sequences that provides units that do not provide comparable samples. For example, a one, two, or three, or four-week sample in January can't be considered as equivalent to another similar sample selected in April. A system of randomization that reverses randomized period from year to year isn't very satisfactory either in a program of such relatively short duration. It seems to us that if the project is to be a pilot model of an operational program, it should be designed in such a way that all aspects of the operation--its strengths and weaknesses--are incorporated. The prime consideration then should be to fit the pilot model to an operation and not to a statistical control system.

In addition, if randomization is utilized with other than an entire winter season, the possibility of having an independent check on runoff increases due to the operation based on regional hydrologic comparisons is eliminated. Estimates of the amount of runoff increase can be made for any randomization scheme; however, we feel it is important to have a means for internal verification of the relation between precipitation and runoff.

We have no overriding opinions as to the relative merits to the Bureau of a research or operationally oriented pilot model program. It is my personal opinion that more could be accomplished by proceeding with an operational program in pilot model form with the best techniques incorporated in it to identify the water produced but to allow for a maximum of continued learning. I believe that one of the major objectives of such a pilot program is to evaluate the evaluation procedure, or more properly, the water identification procedures and learning techniques under operational conditions. This is one of the major reasons for calling it a pilot model rather than a full operation. Proceeding with an operational program certainly doesn't underestimate the importance of research and experimentation. The Bureau already has four technically correct randomized projects in progress in the Rocky Mountain area in addition to the Climax randomized studies. The Montana program is proceeding with efficiency, especially considering their limited resources, and should provide a test of seeding under colder conditions and add a new dimension by testing the effects at lower elevations than have been tested at Climax or Wolf Creek. I understand indirectly that the similar type experiment in New Mexico under the warmer environment is also well underway. In addition the Utah State experiment should be or about to start. With these experimental type randomized programs plus the Park Range randomized experiment, it would appear that another primarily randomized pilot program would almost be an over-kill. It seems to me that the pilot program could serve best the Bureau's purposes by extending its objectives to the more directly operational aspects.

A second item that I would like to make a few comments on concerns the placement of generators. We, of course, are carrying forward the work in this connection. I was a little concerned at the meeting on Tuesday when Jerry Price did not mention the temperature profiles in the observational program now underway by Western. I now assume that this is well in hand. This information, along with the radiosondes that are scheduled to be taken in the Upper basin are vital input in the diffusion model considerations for the placement of the generators.

Charlie and I would like to suggest that representative GMD soundings during the next month be made from between Bond and Wolcott but nearer to Wolcott, from just south of Kremmling, and, a few from near Granby. Representative soundings should include soundings made during a variety of weather conditions, primarily during good cloud situations but also including a few under clear skies and at various times of day and night.

The Climax diffusion model is due to go back into Jack Cermak's wind tunnel the last week of this month and the first week or two of March. We are expecting that we will get some key reference points between the model and some of the prototype field observations at Climax. These should tell us just how much the laboratory model can help. I fully expect that the answer will be that it can be of substantial benefit. For example, we have already learned a number of things about the flow of the materials into the Climax area that we had never expected. The model showed clearly, for example, that despite the fact that we have consistently been able to detect the seeding materials at Climax, the main surge of the seeding plume was not, in fact, through the Climax Pass area, but further west through the Tennessee Pass area and is much broader than we had thought. It appears that this wind tunnel finding is basically correct. My opinion at this stage is that modeling of the pilot project area should very definitely provide substantial information, as a minimum, on the horizontal dispersion of the seeding materials and provide a lot of information on the relative merits of releases from alternate locations in and upwind of the target area. As a maximum, the model could also provide considerable detail on the vertical distributions. The modeling of the pilot area, Jack Cermak tells me, would cost somewhere in the vicinity of $20,000 to $30,000. This seems to me to be a rather minor cost in relation to the detail it could provide before the program starts, and in relation to what it would cost to obtain the same information with aircraft or ground crews. We do want to hold in reservation any firm opinions on this until around the middle of March when we have been able to make this next set of laboratory-prototype comparisons from the present modeling work and have had a chance to go over some of the temperature profiles and soundings presently being taken by Western. The delays in specifying generator sites should not seriously hinder your bid-letting, since it will be possible well before that time to provide you with information on the general numbers and complexity of installation of seeding generators that seems appropriate.

I want to make a few comments on a third aspect of the design. This involves the accretion term in the optimizing models for precipitation over the Colorado Rockies. We, of course, are familiar with the manner in which this term has been used in some models and definitely plan to incorporate it in the operating model for the Colorado River Basin. The fact that nature relies heavily on accretion for the removal of condensate from a cloud does not in itself necessarily mean that we should fall back on this process when we're designing for an optimization process of utilizing water condensate over the Rocky Mountains. An optimizing condition for the use of water from orographic clouds requires an output of liquid and solid water equal the input in condensate. The general form of the relationship then should be

$$I_c = O_d + O_{acc} + R$$

where I_c = Input condensate formed in lifting the airmass over mountains

O_d = Output-precipitation formed by the diffusion growth of ice particles

O_{acc} = Output-water removed by the accretion of cloud droplets to ice crystals having their original growth by diffusion

R = Remainder--water lost to precipitation through inefficient processes and reevaporated to the atmosphere

The fact that nature relies on the accretion term and frequently has loss, R, in addition attests to the deficiency of naturally forming ice nuclei that can use the condensate by the diffusion or O_d process. The accretion represents a process by which condensate can be utilized that otherwise might not be used to form useful precipitation. The remainder represents condensate that escapes use by both the O_d and the O_{acc} processes. The question becomes one of evaluating the efficiency of the O_d, the diffusional growth, and O_{acc}, the accretion growth, processes for Colorado River cloud systems. <u>In an artificial control of the condensate the most desirable course may not be that which relies on the accretion term despite its importance in the natural process.</u> Our primary concern is to minimize the remainder, or loss term. If the condensate can all be used up in the diffusional growth term by optimizing the N_{opt} term in our basic model, there is certainly no condensate left for the remainder term even though the accretion process has been by-passed. You will remember that our basic model of

$$N_{opt} \simeq \frac{V_z}{16.8rG}\left(\frac{WS\ 700 - WS\ 500}{Z_{500} - Z_{700}}\right)$$

is based on full use of the moisture by the diffusional process. We feel that every effort should be made to utilize all of the condensate through this diffusional process if at all possible. This would apply to lower elevations in the southern portions of the basin as well as in the Climax area. Our calculations to date indicate that a process relying on molecular diffusion from the cloud water droplet to the ice crystal stands a much higher chance of being successful in using up all the condensate. (This requires, of course, that the proper number of N_{opt} nuclei have been supplied.) An accretion process requires the chance encounter of ice crystals falling through the field of cloud droplets and the cloud droplets. This efficiency collection is zero for ice crystal sizes less than 200 - 400μ (depending on shape of crystal and size distribution of cloud droplets) and less than 1 for most other conditions experienced in Rocky Mountain orographic clouds. Accretion serves a very satisfactory purpose in picking up part of the water that otherwise would be lost to useful precip[illegible]tion when the concentration of ice crystals is ins[illegible]ficient to use all the condensate by the diffusion[illegible] growth process. The critical ice crystal size i[illegible] furthermore dependent upon its shape. It appears reaonsable in the mountain areas of the Colorado River Basin in winter that programs can be planned to utilize nearly all the precipitation in the diffusional growth process. The critical size for collection before any accretion starts, in the case of columns, is at about 200 microns for the long axis of columns and with a diameter somewhere between 300 and 400 microns in the case of plates. A major portion of the snowfall in the Colorado River Basin at elevations above the 9500 feet in which we are interested, occurs at or below these sizes even naturally. Consequently, a program to generally get the condensate out in particles of these sizes is not unreasonable. These particle sizes do have sufficient fall velocity in general to settle into the mountain areas in which we are concerned.

There are two obvious cases when one would want to fall back on the accretion process:

1. When the particle size would be critically small so that fallout would occur beyond the area of interest or not at all before evaporation sets in. In other words, we might want to utilize the accretion process to help solve a particular targeting problem. The higher fall velocities of the rimed crystals might be utilized to maximize the precipitation as near the upwind portion of the cloud as possible.
2. The other case would be one in which the optimum number of ice crystals required for a very warm cloud, say in the -5° to -10° range, would require such a large value of N_{opt} in the temperature range where the generators are not very efficient, that the economic cost of the operation would become disproportionately large. The solution to this problem probably lies in more efficient generators at the warm temperatures. In most portions of the Colorado River Basin in most cases nearly all parcels of air cool to at least -10° C at some time in their transit over the mountains. Generally a parcel cools even colder than this making the seeding easier and more economical to carry out. Our model evaluation and development program should clarify and specify the efficiency and economic level for the alternate processes.

While I have written this letter, it represents equally the opinions of Paul, Charlie and myself.

An interesting look at the costs of snow removal prepared by Homer Stockwell is attached.

I'll call you when I get back from California. Charlie and Paul will be here next week if you want to discuss any of these or other items.

Sincerely yours,

Lewis O. Grant
Associate Professor

DBNR

February 26, 1969

Dr. Archie M. Kahan, Chief
Office of Atmospheric Water Resources
U.S. Bureau of Reclamation
Denver Federal Center, Building 67
Denver, Colorado 80225

Dear Archie:

This letter is intended to summarize our discussions yesterday (February 25) and to serve as a supplement to the first portion of my February 14 letter to your office. Since this is a supplement to the February 14 letter, a copy of that letter is attached for ready reference. As discussed yesterday, the basic goal of the pilot project is to establish, at a reasonable level of confidence, that weather modification in the Colorado River Basin can produce at least a specific amount of additional water at a cost not exceeding a specific figure. The accomplishment of this objective requires:

1. A determination of the most likely amount of water added from a specific treatment.
2. A determination of the cost of the treatment.
3. A verification that a treatment efficiency at least equal to that in past experimental programs can be obtained in a full-scale operational program.

The successful accomplishment of these three goals in a single project presents certain problems. An operational-type program for establishing costs and treatment efficiencies is not necessarily the type of program that lends itself to the most precise estimate of the amount of water added. Unbiased estimates of the effect of seeding, I believe, do require the incorporation of randomization to collect a sizeable sample of seeded and unseeded events. Furthermore, the experimental unit used in an experimental project is critical to its success. The use of an interval much longer than the day precludes the possibility of stratifying according to critically different meteorological conditions. An experimental unit substantially shorter than the day can: (1) Cause residual contamination in the unseeded period from a previously seeded period unless non-experimental buffer periods are also included; (2) Increase the observational problem with the low snowfall rates generally experienced in the Colorado Rockies; and (3) Give a very complex and even biased, if tests are not run at all hours, sample, since the natural diurnal variation of precipitation in the Colorado Rockies is so large. The large natural variability and the undefined trends in natural precipitation combined with the relatively small magnitudes of artificial changes make the randomization essential for making confident estimates of the artificial changes. On the other hand, randomization procedures which leave substantial portions of precipitation-producing situations unseeded are not very desirable in an operational program for increasing water supplies through the use of weather modification. This is particularly true in the Colorado River Basin where the artificially-added increments must be obtained from relatively small increments of precipitation on a rather large number of days.

The design for the pilot project presently being considered represents an approach for accomplishing the three specific aspects of the basic goal in a single pilot project. Since it does represent a full-scale field operation, it is clearly amenable to accounting procedures to establish costs. It is also suitable for establishing some aspect of the treatment efficiency, namely, timing of the operations, verifications that the equipment ran properly under field conditions, and that at least under some circumstances the seeding materials did arrive in the intended target. The efficiency of treatment, probably relatively low in most operational programs of weather modification, becomes even more critical as differentiation between favorable and detrimental events must be made. The design provides for alternate methods for estimating the amounts of water added. In addition, comparisons of these estimates can be made with those obtained under experimental-type programs as a further verification of the treatment efficiency. All of the alternate methods suggested for evaluation of a pilot project of operational seeding might involve more risk than an evaluation obtained from a purely randomized experiment. On the other hand, they should, in combination with the results from the five experimental-type projects underway in the intermountain area, provide estimates of the water added at a risk level, that for most purposes, would not be considered excessive. Two of the methods proposed (3 and 4 below) could provide information that would not be as readily obtained from a strictly randomized experiment to determine changes in precipitation. Furthermore, the risk of residual effects from the seeding on closely associated unseeded days is eliminated.

The following is a brief summary of the alternate methods being suggested for determination of the water added in a pilot project:

1. <u>Extrapolation from Experimental Type Projects</u>

   A first estimate of the water added can be obtained by applying the results of changes in precipitation determined in nearby experimental projects for the range of meteorological events actually seeded in the pilot project. In future fully operational programs such extrapolations will most likely be the primary method used in identifying water added from seeding operations.

2. <u>Determination of Changes in Precipitation Using Statistical Techniques</u>

   Target and control relationships for precipitation frequently serve as the basis for determining changes in precipitation in a target area. This procedure involves the establishment of a relationship between the target and control for an historical period and a comparison of this relationship to that which results during the seeded period. The obvious danger in such a procedure is that the relationship may have changed naturally between the historical and seeded periods. Furthermore, the procedure requires a large sample of historical and seeded data. The second method proposed for evaluating the pilot project relies on essentially this procedure but does allow for the collection of the seeded and unseeded sample as the program progresses and reduces some of the risk of natural long-term changes in the target-control relationship between the seeded and unseeded periods.

It is proposed that two sub-areas in the Colorado River Basin be selected and instrumented. One or the other of these two sub-areas would be seeded during each of four winter seasons according to block randomization that would permit each to be seeded two years and left unseeded two years. Despite the fact that the randomization would be made on an annual basis, most evaluations would be made on the basis of a shorter time interval, such as the calendar day. This, of course, would not preclude evaluations on an annual basis and comparison with historical data. With the analyses made on the basis of the calendar day, the four-year program would provide approximately 200 seeded and 200 non-seeded days in each of the sub-areas. This procedure does have the disadvantage that seeded and unseeded days are not being randomly distributed through all four years. This represents a compromise being made to the operational-type program. Preliminary analyses of Colorado mountain precipitation data show that the frequency distribution of shorter periods, such as the calendar day, precipitation is reasonably stable from year to year despite larger variations in total precipitation that occur. A check is provided against some catastrophic change in the distribution of daily precipitation by the control areas and by the fact that such a change would show up in one area in the seeded sequence and the other sub-area in the unseeded sequence. Some confidence in such a procedure has been gained from comparing the results of such an experiment in the Wolf Creek Pass area to the results obtained in the purely randomized Climax experiment. The results obtained from four years of seeding with 360 seeded and non-seeded events are essentially the same as those obtained in the Climax experiment and are consistent with results expected from a physical model of the precipitation processes.

3. Hydrology

A frequently used evaluation procedure for weather modification in the western U. S. has been the comparison of hydrologic relationships in a seeded period with historical hydrologic relationships. This procedure, as in the case of precipitation, has the disadvantage of incorporating an uncertainty as to whether there may have been a natural change in the relationship between the seeded and unseeded periods. It has the additional disadvantage of having the precipitation exposed in the form of snow to other controls, such as wind and evaporation, for many months before being converted into water for usable streamflow. This approach does have the advantage to the user of weather modification in that the evaluation is in terms of water in the stream which represents his primary interest. If care is used in establishing the relationships, reasonably high correlations of the order of .8 to .9 with control watersheds can usually be attained. It is not practical to use this procedure in a fully randomized experiment with a short experimental unit since the streamflow hydrograph is dominated by an annual peak caused by the integration of all of the shorter interval precipitation amounts.

4. Atmospheric Water Balance

A fourth evaluation procedure suggested employs techniques for determining the efficiency with which water vapor is utilized in the production of precipitation while traversing the pilot project area during both seeded and unseeded events. This admittedly is a largely untested technique. However, Dr. Rasmussen has shown that, for the entire Colorado River Basin, estimates of water yield comparable to the best obtained with precipitation measurements and snow depth measurements can be obtained. These calculations were made using only the presently available very sparse radiosonde stations which take observations only twice each day. The use of supplemental radiosonde data at intervals more frequent than 12 hours should at least offset the greater complexity of using this procedure on a smaller area such as a sub-basin.

5. Physical Evaluation

A physical evaluation of a model, that has in general form been verified by experimental-type seeding experiments, can provide useful information as to the conclusions that precipitation changes as suggested by the model are being obtained. This procedure, of course, cannot be used to obtain detailed estimates of the amount of water added. It can, however, serve a useful purpose in backing up the results obtained from the other evaluation procedures from which such an estimate of added water can be made.

Good statistical estimates of the differences in precipitation and streamflow between seeded and unseeded events can be made using the above evaluation procedures. These procedures do not completely eliminate the possibility that some fundamental atmospheric change has occurred and that a difference in precipitation and streamflow has resulted from this change rather than from the seeding. It is virtually impossible to specify a figure for this risk since the risk factor, by its very nature, is undefined, and as such cannot be precisely evaluated. The suggested evaluation procedures do incorporate strong guideposts for detecting the possibility that such catastrophic changes may have occurred. In combination, they leave only a small risk that estimates of the seeding effect obtained by these methods would not be reasonable.

Sincerely yours,

Lewis O. Grant
Associate Professor

September 4, 1969

Mr. Pat Hurley
Office of Atmospheric Water Resources
U.S. Bureau of Reclamation
Denver Federal Center, Building 67
Denver, Colorado 80225

Dear Pat:

This letter includes our comments on the different sites chosen by Western Scientific Services for the various meteorological observations that will be initiated this coming winter season.

I. Telemetered Weather Stations
   A. Ground Hog Mountain
   B. Runlett Park
   C. Blackhead Mountain

   As discussed before, these sites do not represent our first choice. However, after discussions with Western, we agree these sites probably best compromise the various meteorological, economic, and safety factors involved. While it was not clear at the time I talked to Western, it is assumed that these telemetered stations will include temperature and relative humidity as well as wind direction and speed as minimum of observations.

II. Recording Wind Stations
   A. North Mountain
   B. Molas Divide
   C. Runlett Park
   D. Top Wolf Creek Ski Area

   We are in agreement with these locations. Site position at the respective locations can be quite important. Efforts should be made to obtain free air exposure to the extent feasible.

III. Recording Hygrothermographs
   A. Wolf Creek (861)
      Wolf Creek Summit
   B. Berri Park
      Runlett Park
   C. Coal Bank
      Molas Divide

   We are in agreement with these sites. It would appear to require a minimum of expense and effort to also run a hygrothermograph at North Mountain, since you plan a wind station at that site.

IV. Pibals
   A. Dolores
   B. Chromo

   We are in agreement with these sites. It is believed that a Pagosa Springs site would yield useful information, especially since it now appears that the Wolf Creek Pass area will be modeled in the wind tunnel. It is believed that supplemental pibal and constant density balloon runs from Pagosa Springs should be taken as information pertinent to this modeling problem.

V. Ice Nuclei and Crystal Replication Data
   A. Ice Nuclei Counters
      1. Dolores
      2. Silverton
      3. Chromo
   B. Crystal Replicators
      1. Wolf Creek Summit
      2. Top Purgatory Ski Lift
      3. Rico

   We would like to suggest a different arrangement for the ice nuclei counters and crystal replicators. It is believed that the ice nuclei locations suggested will be frequently affected by seeding and therefore none would be suitable as a control. In order to further study and verify the cloud physics model, it is important that the ice nuclei counters and crystal replicators be placed in locations relevant to these goals.

   We would like to see an upwind control station established at Mesa Verde. This location has the advantage that it is located far enough southwest to serve as a control and the higher elevations of the park are highly desirable from the standpoint of sampling ice nuclei and ice crystals. We recommend if at all possible, ice nuclei, ice crystal and other supporting data be taken at Mesa Verde.

   We would also like to have observations of ice nuclei and ice crystals taken from the same site near the summit of Wolf Creek. While we would prefer the Wolf Creek Summit location, the present Wolf Creek West location is an acceptable second choice.

   Ice crystal data is also needed on the east side of Wolf Creek Pass. This is desired in the general area extending from the Wolf Creek East recording gage down to the chain station.

   Ice nuclei and ice crystal data is also needed on the west side of Wolf Creek Pass, preferably in the general area extending between Four Mile Creek and Turkey Creek. If this becomes impossible, Pagosa Springs would be a less desirable second choice.

   You will note the above suggestions require three ice nuclei counters and four ice crystal replicators. This is one more replicator than originally proposed by Western. It is hoped that this additional replicator might be made available.

VI. Rawinsonde Data
   A. Durango

   We are in agreement with the proposed rawinsonde location at Durango. We would really very much like to have some additional radiosonde runs for at least one month (preferably January) to be run east of the Divide. This would enable

Rasmussen and Riehl to make atmospheric water balance computations and evaluations untilizing Grand Junction, Climax, Durango, and the proposed station east of the Divide. Data from the additionally proposed radiosonde would enable the evaluation of line integral techniques and also two dimensional techniques over Wolf Creek Pass. It is believed that data from a normal winter month would be sufficient and if necessary, Colorado State University could supply a portable radiosonde after pre-Christmas activities at Climax.

It is believed that the general area extending from Monte Vista westward to Del Norte and South Fork would be best for this additional site. Some reconnaissance could be done in December in order to pick a site least troubled by the low stratus which tends to form with the cold pooling in the San Luis Valley. Pibals might then be included with these runs during the month's activities.

These are our thoughts and preferences on the disposition of the various instrumentation in the San Juan area. I am enclosing a copy of this letter to Western to expedite matters.

A letter outlining proposed activities for this coming winter should follow in a day or two along with the preliminary copy of the annual report.

Sincerely,

Charles F. Chappell
Research Meteorologist

cc Western Scientific Services, Inc.

September 8, 1969

Mr. Pat Hurley
Office of Atmospheric Water Resources
U.S. Bureau of Reclamation
Denver Federal Center, Building 67
Denver, Colorado 80225

Dear Pat:

The following represent our ideas and suggestions for work that might be completed by the Seeding Contractor this coming winter season relevant to the San Juan Pilot Project. Our suggestions have been developed under the assumption that the seeding contractor will take control of those systems related to the real time control of operations for the Pilot Project. There may be a few areas involved wherein Western Scientific Services will perform the work this coming winter but will turn it over to the seeding contractor for the remainder of the project (such as the rawinsonde work). In this event it will be important for the seeding contractor to spend some time with Western in order to become familiar with the equipment, etc., so that an orderly transfer can be made prior to the beginning of the project in the fall of 1970.

I. Establishment of an Operations Base

The seeding contractor should concentrate on the establishment of an operations base (or bases). This facility should be manned and equipped to provide the following necessary services vital to the operation of the pilot project.

A. Forecast services

Personnel and equipment necessary to provide around-the-clock weather surveillance and forecast support for the pilot project should be established at the operations base. Forecast problems relevant to the pilot project are expected to include: (1) the identification of an "experimental day," (2) short term forecasts of upper winds, temperatures, and moisture distributions pertinent to the real-time control of the operations, and (3) longer range weather outlooks needed for planning field activities such as distributions of supplies, equipment maintenance, etc. Forecast aids and programs pertaining to the identification of an "experimental day" and the determination of modification potential will be made available to the seeding contractor by Colorado State University. The Seeding Contractor should initiate efforts to test and suggest improvements in these for operational use.

B. Operational procedures

It is suggested that the seeding contractor spend some time during the coming winter in establishing operating procedures. This should include include the development of step-by-step procedures for conducting daily operations, the development of necessary forms, the establishment of quality control procedures, etc. These should be agreed on before the actual pilot project starts so that consistency of procedures can be maintained during the course of the program.

C. Testing, maintenance and supply service

Personnel and equipment to provide the testing, maintenance, and supplies necessary for the successful functioning of the pilot project should be an integral part of the Operations base. The seeding contractor should check out and test generators, establish a maintenance shop, workout procedures for field control, and begin securing supplies.

II. Checkout of Operational Control Observation System

It is very important that the observational system, which will be used to control the pilot project on a real-time basis, be completely established, de-bugged and maintained this coming winter. Undoubtedly, problems will arise which are not foreseen at present. It is vital that these be discovered and solved this coming season so that a more smooth operational control can be provided by at least the fall of 1970. Three specific items that should receive attention are:

A. The mountain top weather stations and their associated telemetry should be perfected as much as possible, data obtained, reduced and compared with the existing synoptic network for representativeness and reliability.

B. Rawinsonde data should be taken regularly and compared with the existing synoptic network for representativeness and reliability. Correlations should be run with the existing synoptic network after representativeness has been determined, so that the regular synoptic network could be substituted more accurately should breakdown occur.

C. If any of this work is to be done by Western this winter but be taken over by the seeding contractor in subsequent years, the seeding contractor should provide some minimum time and manpower to become completely familiar with the equipment and its maintenance. This would include trips to the instrumentation for maintenance purposes, etc.

III. Generator Site Reconnaissance and Related Work

It is believed that the seeding contractor this coming winter might perform some useful work related to the ultimate placement of generators. This work would constitute the determination of local air flow characteristics, studies of local cold air pooling problems, tracer studies that could be compared with forthcoming wind tunnel results, and generator site reconnaissance.

IV. Operations

It is believed desirable that the seeding contractor should "dry run" as much of his operations as is possible during the last half of the season. This would include checking out the control observational system, operating procedures, generators, etc., under actual field conditions. The more he is able to do these things this coming winter, the smoother the operations should function the first year of the project. If this "dry run" program is successfully completed before the end of the season, actual operations could be initiated.

It appears the seeding contractor will be working very closely not only with Western but also with our design group at Colorado State University. It is considered highly desirable that the seeding contractor make a man available (at least on a part-time basis) for coordination with the CSU effort during the coming year. This will not only provide for a good understanding between the design group and the seeding group but will allow the seeding contractor to become completely familiar with those aspects of the design which will bear on his operating procedures and requirements. It would be desirable that this individual have a broad technical background since this coordination will also provide the seeding contractor opportunity to provide input into the operational design.

These are some of the suggestions we have on the work of the seeding contractor this coming winter. Please let us know if additional specific information would be helpful at this time.

Sincerely yours,

Charles F. Chappell
Research Meteorologist