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# DESIGN OF PHYSICAL CLOUD SEEDING EXPERIMENTS FOR THE ARIZONA ATMOSPHERIC MODIFICATION RESEARCH PROGRAM

## FINAL REPORT

PREPARED FOR

ARIZONA DEPARTMENT OF
WATER RESOURCES

UNDER IGA-89-6189-450-0125

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U.S. DEPARTMENT OF THE INTERIOR
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Arlin B. Super, Jon G. Medina,
and Jack T. McPartland

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16. ABSTRACT

Cloud seeding experiments have been designed by the Bureau of Reclamation for winter orographic cloud systems over the Mogollon Rim of Arizona. The experiments are intended to test whether key physical processes proceed as hypothesized during both ground-based and aircraft seeding with silver iodide. The experiments are also intended to document each significant link in the chain of physical events following release of seeding material up to, and including, snowfall at the ground at a small research area about 60 km south-southeast of Flagstaff. The physical experimentation should lead to a substantially improved understanding of winter seeding potential in clouds over Arizona's higher terrain. Such understanding and documentation are a logical prelude to any future experimentation intended to determine seeding impacts over a large area during several winters. Several analysis approaches are suggested to evaluate the physical experiments which range from detailed case study examination to exploratory statistical analysis of experiments pooled into similar classes. Experimental coordination and organization are addressed, and budgets are presented for a 5-year program estimated to have a total cost of $9.5 million.

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*b. IDENTIFIERS--* Mogollon Rim/ Happy Jack/ Hannagan Meadow/ White Mountains/ Flagstaff/ Alpine/ Payson/ Conconino National Forest/ Prescott National Forest/ Camp Verde/ Winslow/ Arizona

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UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

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# EXECUTIVE SUMMARY

This report documents planning for comprehensive physical cloud seeding experiments to be conducted on the Mogollon Rim of Arizona. The goal of these experiments is to validate hypothesized physical processes following seeding. The planning included the development of (1) experimental designs for both ground-based and airborne seeding of winter clouds, (2) analysis approaches to be applied to the resulting measurements, and (3) cost estimates for the overall program. The entire physical experiment program, from equipment procurement and contracting through field observations, final analysis and reporting, would require 5 years. This assumes a separate analysis group will work simultaneously with the field group and that measurement programs will be carried out during years 2 through 4. The total cost of the 5-year program is estimated to be $9.5 million.

Past attempts at physical seeding experiments with winter clouds were reviewed and briefly described. Some common factors affecting either success or failure were identified. For example, airborne identification and tracking of the seeded volume were very important in the successful experiments, especially in the complex airflow near mountains. These factors require that mountain experimental areas be carefully chosen to permit low level aircraft sampling during storms. Changes in ice particle concentration were the most detectable characteristic of seeding at ground level. Frequent monitoring of the silver content of the snowfall helped validate targeting in silver iodide (AgI) seeding experiments. Negative factors included attempts to "piggy-back" physical experiments on statistical designs and inadequate analysis during and between observational programs so that needed design improvements were recognized too late.

The entire Mogollon Rim, from near Flagstaff to the White Mountains on the New Mexico border, was considered in choosing an experimental area for physical seeding experiments. By a process of elimination the "best" target site was determined to be Allen Lake, 60 km south-southeast of Flagstaff. It is near the rim's crest, has few peaks to interfere with low level flight, has good road access and electrical power, and is in a large enough clearing for operation of key instrumentation systems. A Doppler weather radar could be operated north of Allen Lake in a position that would permit scanning from cloud tops to near the ground. The project operations center would be colocated with the radar while project aircraft would be based at Scottsdale.

The various scientific uncertainties concerning Arizona winter clouds are addressed. These include limited knowledge of the spatial and temporal distributions of supercooled liquid water over the rim, and of ice crystal formation, growth and fallout trajectories, especially when many crystals aggregate into large snowflakes. Whether conditions exist such that seeding might sometimes reduce snowfall is an open question. These and other important issues will be investigated during the course of the experimental program.

Several sophisticated observing systems are recommended for use in the physical experiments. These include a microwave radiometer for detection of water vapor and liquid water; a Doppler acoustic sounder to monitor winds in the lowest kilometer; a scanning Doppler radar for storm structure, cloud top, and wind observations; two rawinsonde systems to obtain vertical profiles of wind, temperature, and moisture; and various surface sensors including high resolution precipitation gauges and an ice particle imaging probe. An instrumented cloud physics aircraft would monitor the seeding agent and a variety of cloud characteristics. A seeding aircraft would dispense AgI ice nuclei and also make some cloud measurements.

Most experiments would be carried out in extensive, mainly stratiform, cloud systems. Ground-based seeding experiments would use generators located well upwind of Allen Lake to release plumes of AgI intended to merge and be transported over that target site. Repeated crosswind passes would be made by the cloud physics aircraft through the seeded volume, and through neighboring nonseeded cloud. These observations should reveal differences in ice particle concentrations, crystal habits and sizes, and cloud liquid water content between seeded cloud and crosswind natural cloud. The aircraft passes should monitor the AgI plume position so that precipitation rates in gauges likely affected by seeding could be compared with gauges measuring only natural snowfall. The Allen Lake target would have several instruments to monitor snowflake characteristics, very high resolution precipitation rates and silver-in-snow concentrations. Similar observations of nonseeded snow would be made at a crosswind control site. Seeding would continue for up to 3 h per mission after which aircraft sampling would continue as the AgI plume left the area. This procedure would allow natural cloud to be sampled after the seeded cloud volume passes beyond the target.

Airborne seeding experiments would be of two types. One method of seeding would have the seeding aircraft continue to orbit over a fixed point, releasing an AgI plume intended to pass over Allen Lake. The cloud physics aircraft and ground systems would make observations similar to those taken during the ground-based seeding experiments. The other airborne seeding method would release crosswind lines (seedlines) of AgI that would disperse vertically and along-the-wind as they approached the target. Ground instruments would provide comparisons of events before, during, and after passage of each seedline. The cloud physics aircraft would make repeated along-the-wind passes through each seedline and natural cloud upwind and downwind of it. Several seedlines could be released and sampled during a single experimental period. Each seedline would be evaluated by comparison with natural conditions shortly before and after seedline passage over the target.

Additional physical experiments are recommended for convective clouds that are sometimes present over the Mogollon Rim during winter. These would not be seeded but observations would be made to allow estimation of their weather modification potential. Earlier cursory examination of convective clouds suggested they often were too short-lived or naturally efficient to be seedable, but a more detailed study should be done.

Various investigations of a climatological nature are recommended with some of the same observing systems used for physical experiments. The climatological studies would aid in the design of any future randomized seeding experiment intended to demonstrate the magnitude of long-term snowfall augmentation over a large area. A randomized experiment would be the next logical phase if the physical experiments succeed in showing that snowfall can be increased over a small target with sufficient frequency and magnitude. Climatological investigations will allow the brief physical experiments to be considered in the context of general storm conditions over several winters.

Several analysis approaches are suggested ranging from evaluation of the individual physical seeding experiments to general climatological investigations. The individual physical seeding experiments are very important in testing whether key physical processes proceeded as hypothesized. When possible, individual experiments should be pooled into similar classes to allow exploratory statistical analysis on samples with reduced variability, using nonparametric techniques that can be applied to small populations.

Recommended data analysis methods include comparisons of seeded and nonseeded time series of precipitation rate and ice particle concentrations, habits, and sizes. Several existing software packages are suggested for aiding the determination of seeded volumes, and for producing results in easily comprehended graphical displays.

The area likely to be affected by the limited seeding during physical experiments was estimated, as was the amount of the increase. It appeared unlikely that the proposed seeding would have any discernible influence beyond a 20-km radius from Allen Lake. The seasonal increases in this area might range from a maximum of 4 percent to about 1 to 2 percent. Corresponding melted snow precipitation increases during a normal month should be less than 4.5 mm with snow depth increases less than 45 mm. The primary reason why only very small increases are anticipated is that only a small fraction of the total time with storms would be seeded over the course of any winter.

Experimental coordination and organization are addressed. It is recommended that a "nowcasting" rather than a forecasting approach be taken in determining when to commence experiments. That is, current observations of the weather over the Mogollon Rim and that approaching the rim would be used in deciding when to conduct an experiment, and what type to attempt. A single contractor is suggested for all ground-based functions and for operation of the seeding aircraft so all seeding would be the responsibility of a single group. A second contractor should furnish the cloud physics aircraft, which would have a highly specialized function. A third contractor should perform all analysis, design improvements as knowledge is gained, and report scientific findings.

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# GLOSSARY

| | |
|---|---|
| a.g.l. | above ground level |
| ADWR | Arizona Department of Water Resources |
| AgI | silver iodide |
| FAA | Federal Aviation Administration |
| FC | field coordinator |
| FSSP | forward scattering spectrometer probe |
| IFR | instrument flight rule |
| IPC | ice particle concentration |
| JW | Johnson-Williams |
| LWC | liquid water content |
| MC | mesoscale convective |
| MOA | military operating area |
| m.s.t. | mountain standard time |
| NWS | National Weather Service |
| PMS | Particle Measuring Systems, Inc. |
| Reclamation | Bureau of Reclamation |
| RHI | range height indicator |
| SCPP | Sierra Cooperative Pilot Project |
| $SF_6$ | sulfur hexafluoride |
| SHM | Super, Holroyd, and McPartland, 1989 |
| SLW | supercooled liquid water |
| T&D | transport and dispersion |

# CONVERSION FACTORS

| *To convert from* | *To* | *Multiply by* |
|---|---|---|
| centimeters | inches | 3.937 x $10^{-1}$ |
| degrees Celsius | degrees Fahrenheit | 9/5 (then add 32)<br>°F = 9/5 °C + 32 |
| kilometers | miles | 6.214 x $15^{-1}$ |
| liters | gallons | 2.642 x $10^{-1}$ |
| meters | feet | 3.2808 |
| millimeters | inches | 3.937 x $10^{-2}$ |

# 1. PHYSICAL DESIGN AND FIELD OPERATIONS

## 1.1 Introduction

**1.1.1 Background.** - The ADWR (Arizona Department of Water Resources) and Reclamation (the Bureau of Reclamation) have been cooperating since 1985 on an assessment of snowpack augmentation potential known as the Arizona Program. The purpose of the program is to develop a cloud seeding technology capable of enhancing the winter precipitation on the higher portions of Arizona's Mogollon Rim, which in turn can be expected to increase water supply in the local areas for direct use and ground-water recharge and to increase streamflow. The technology must be scientifically sound and socially acceptable, the latter implying that no significant deleterious environmental consequences result. Both ADWR and Reclamation want to proceed in a methodical fashion, documenting the extent to which cloud seeding can enhance Arizona's limited water supplies, and the social and environmental consequences of the seeding, prior to any consideration of operational seeding.

The first effort under the Arizona Program was a feasibility study (Reclamation, 1987), which investigated Arizona winter cloud seeding potential and ramifications using existing data sources. It was recognized at the onset that such a study would not yield conclusive answers, but the investigations did find reasons for optimism concerning cloud seeding potential, and laid the framework for further onsite studies. A number of approaches were suggested for further work.

Two-month field efforts were conducted at two different sites on the Mogollon Rim during early 1987 and early 1988, respectively. These measurement programs were intended to document the characteristics of winter clouds and precipitation with emphasis on the availability of SLW (supercooled liquid water), which is required for seeding to have any practical potential. The feasibility of seeding with ground-based AgI generators was also addressed using a tracer gas. No cloud seeding was conducted during these field programs.

A final report by Super et al. (1989) discussed the findings of the two field programs. Briefly, SLW was observed during portions of most storm episodes. The winter total flux of SLW was estimated at 30 to 100 percent of the mean annual streamflow from high elevation watersheds, suggesting that this necessary (but not sufficient) ingredient for cloud seeding to succeed is available in relative abundance. The SLW was concentrated in a few large storms that were naturally efficient in snowfall production during portions of their passage, but inefficient during other storm stages. The seeding simulation studies revealed that ground-released seeding material would usually reach the lower cloud regions where much of the SLW is found, but temperatures would frequently be too warm for formation of many ice crystals using conventional types of AgI and generators. It was recommended that experiments be designed to document results of particular seeding treatments, including field testing of recently developed types of AgI which produce significant ice crystal concentrations in cloud chambers warmer than $-10$ °C.

**1.1.2 Future Investigations.** - Analyses of the 1987 and 1988 field observations have indicated winter cloud seeding potential likely exists over the Mogollon Rim. The next step for the Arizona Program is to demonstrate, with convincing physical evidence, that particular seeding approaches applied to specific cloud types can augment precipitation on the surface at a preselected target site. The goal of this report is to provide practical experimental designs and subsequent analysis approaches that should provide a credible demonstration of seeding effectiveness. If the proposed physical experiments succeed, a logical followup phase would be to design and conduct a randomized seeding experiment to permit statistical evaluation of seeding effectiveness over a number of winters and over large target areas. Presuming the statistical phase was also successful, Arizona would then be in a position to evaluate whether to commence with operational seeding aimed at enhancing the water resources of the Mogollon Rim. By then the achievable magnitude of precipitation augmentation should be known, along with associated costs and benefits.

**1.1.3 Purpose of Physical Experiments.** - This report discusses the results of Reclamation efforts on the Arizona Program from early 1989 to early 1990. The goal of these efforts was to design comprehensive physical cloud seeding experiments and subsequent analysis approaches for the Mogollon Rim. The experiments are intended to document each significant link in the chain of physical events following release of seeding material up to, and including, snowfall at the ground. Sufficient measurements will be made to permit examination of each experiment concerning its success or failure to enhance snowfall in a small predetermined target area. As stated by Hobbs and Radke (1975), "In carrying out a *physical evaluation* the objective is to record a chain of events, from cloud to ground, which are consistent with the predicted effects of artificial seeding and which produce perturbations which are distinct from those to be expected naturally." Hobbs (1975a) noted that physical experiments are not intended to replace statistical experiments, which are needed to evaluate the effects of seeding many storms over a large target area, but are a logical precursor that greatly aid design and evaluation of later statistical experiments. Braham (1981) also makes a strong case for improving our understanding of the physical processes in clouds and their reactions to seeding before conducting any more large field experiments aimed at demonstrating surface precipitation changes while ignoring intermediate processes.

## 1.2 Past Attempts At Physical Seeding Experiments

**1.2.1 Historic Overview.** - Physical changes caused by seeding supercooled clouds were obvious in the first cold box experiments by Schaefer that started scientific weather modification (Schaefer, 1946). Later the same year Schaefer scattered dry ice along a line over a stratiform supercooled cloud deck, which quickly converted into snowflakes that fell about 600 m before sublimating (Schaefer, 1953). Several photographs from the late 1940's show portions of supercooled stratus cloud converted into ice crystals. Thus, physical evidence that seeding can convert supercooled cloud into ice particles is available from the earliest work in scientific weather modification. However, it has proven to be much more difficult to obtain physical evidence that seeding initiates a complex chain of events which finally affects surface precipitation.

Much cloud seeding experimentation of the 1950's and 1960's was statistical in nature, with clouds seeded or left as control cases based on random decision. The experiments were usually of the "black box" type, in which seeding material was released and precipitation was monitored but the intervening physical processes were not routinely observed because of limitations in instrumentation. While some of these experiments strongly suggested precipitation changes (increases or decreases) related to seeding, not one is widely accepted as having provided scientific proof that such modification occurred. Byers (1974) presented a history of this period.

**1.2.2 Overview of Physical Experiments.** - A number of reports and publications will be cited which describe attempts to conduct comprehensive physical cloud seeding experiments. Such experiments, hereafter called physical experiments, strive to document most or all of the key physical processes hypothesized to follow the release of the seeding agent. These processes include the transport and dispersion of the agent into the intended volume of cloud, creation of an appropriate concentration of ice crystals, initial diffusional growth of the crystals, possible further growth by accretion and aggregation, and settling of the snowflakes to the surface. All of these processes are time dependent, several are dependent upon temperature and/or moisture content, and all occur in a complex three-dimensional airflow regime. Added to these complexities are the difficulties of direct sampling in the lowest kilometer above mountainous terrain where recent investigations indicate most of the SLW is concentrated (Hill, 1986). It is, therefore, not surprising that many physical experiments over mountain barriers have failed to demonstrate that seeding leads to enhanced snowfall. A review of the complex processes involved, what has been learned about them in recent years, and what remains uncertain is given by Reynolds (1988).

**1.2.3 Great Lakes Experiments.** - A series of notable physical experiments was carried out from 1968-1972 as part of the Great Lakes overseeding project summarized by Weickmann (1974). Holroyd and Jiusto (1971) reported on one case in which an aircraft-released line of AgI resulted in marked changes in IPC (ice particle concentration) at a surface site 28 km downwind. The basic approach was to examine the time history of IPC. This alone would not be sufficient to demonstrate a seeding effect, but the increase in IPC was in agreement with the arrival time expected from the prevailing windspeed, and the enhanced IPC was associated with above background levels of iodide. A slight but not statistically significant increase in precipitation rate corresponded with the passage of the seeded cloud. Other similar experiments were reported by Jiusto and Holroyd (1970).

Eadie's (1970) discussion of the Great Lakes experiments pointed out that snowfall distributions were highly variable, making it very difficult to isolate seeding effects from natural variations occurring on the same time and space scales. He recommended aircraft sampling of the clouds and a number of mobile ground observation stations.

Weickmann (1973) presented a comprehensive report on the Great Lakes experiments. He concluded that, "This research constitutes one of the few available studies that have shown unambiguously without postexperimental data manipulation that artificial precipitation can be generated, and that cases in which 'nature misses her chance' do occur often enough to warrant continued exploration." Numerical modeling of the clouds and their response to seeding was an important component of this project. However, the real strength was that many of the case study experiments were able to track the seeded cloud volume. This was done by using visual observations from aircraft, by monitoring the AgI, and by radar measurements, so that it was known when the seeded cloud passed over the ground observing sites. Surface measurements of ice crystal characteristics, especially of IPC, revealed temporal changes that were associated with the seeded cloud passage. In addition, AgI particles were identified in the seeded snow. However, in spite of successfully following physical processes from release of seeding material to snow on the ground, quantitative measurements of snowfall rate were not achieved.

**1.2.4 Bridger Range Experiments.** - Super et al. (1972) described several attempts to directly detect the effects of seeding on the Bridger Range of Montana. Both airborne and ground seeding were done, and radar and various surface measurements were made in the target area. The radar was very useful in providing wind information for targeting, by tracking reflectors on balloons. However, changes in radar reflectivity due to seeding were inconclusive except in nonprecipitating situations. Changes in IPC with time appeared to be the strongest evidence of seeding effects, but natural temporal changes often made interpretation difficult. It was recommended that additional surface stations be operated crosswind of the target to help monitor natural changes with time. No instrumented aircraft was available to track seeded cloud volumes during these experiments, which proved to be a serious shortcoming.

Considerable credibility was added to the results of an earlier exploratory statistical experiment reported by Super and Heimbach (1983) and by the physical observations reported by Super and Heimbach (1988) for the Bridger Range. One of the high-altitude seeding generators used in the statistical experiment was again operated and low-level aircraft observations were made in-cloud over the target area. The basic approach was to fly normal to the wind, attempting to intercept the plume of AgI seeding material as measured by an acoustical ice nucleus counter. Ice crystal size spectra, habits, and IPC were monitored within and immediately crosswind of the seeded volume The natural cloud on either side of the seeded cloud provided an almost simultaneous basis of comparison, or control, for testing seeding effects. Dramatic increases in IPC and estimated precipitation rate were found when the cloud contained SLW while no changes were found in the absence of SLW. Unfortunately, resources were not sufficient for ground observations under the seeded volume so the final step in the chain of physical events, snowfall on the surface, was not documented. However, all available observations indicated that surface precipitation should have been increased.

**1.2.5 Cascade Project Experiments.** - Among the most convincing physical experiments, and certainly a pioneering program for development of new instruments and approaches, was the Cascade Project work reported in the three part series by Hobbs (1975a), Hobbs and Radke (1975), and Hobbs (1975b). Observations were made over the Cascade Mountains of Washington State during the winters of 1969-70, 1971-72, and 1972-73. A well-instrumented aircraft released seeding material and observed resulting changes in clouds, which were usually stratocumulus. Seeding was done with the aid of a targeting scheme intended to affect snowfall at a small predetermined target area. Seeded cloud volumes were tracked by aircraft, using visual observations and measurements of ice nuclei and ice crystals. A vertical-pointing Doppler radar monitored the spectra of fallspeeds of precipitation particles. Manned ground stations provided ice particle observations and measurements of snowfall rate. Snow samples were analyzed for silver content and concentrations of freezing nuclei. All together, these comprehensive physical measurements often revealed a consistent portrayal of seeding effects reaching the intended surface target. Reference was made to 20 case studies from 1971-72 for which the effects of seeding were clearly detected by 1 or more airborne techniques in 80 percent of the cases, with possible verification in all other cases. For the same cases, distinct evidence of seeding was seen on the ground on 6 occasions, suggestive evidence on 4 occasions, and no evidence in the other 10 cases.

Further physical evidence of seeding effects was presented by Hobbs et al. (1981). Three dry ice seeding lines were placed across the wind in a nonprecipitating altocumulus cloud deck. Aircraft measurements clearly demonstrated an increase in larger particles in the seeded volumes compared with nearby nonseeded cloud. This was verified by radar which showed increased reflectivities from each seedline. The third seedline, released furthest upwind, resulted in a trace of snowfall at the radar. No snowfall reached the radar from the earlier seedings. Each of the seedlines passed over the radar within a few minutes of the estimated time of arrival based on the wind velocity.

**1.2.6 Grand Mesa Experiments.** - A comprehensive set of measurements was obtained in the physical experiments done over the Grand Mesa of Colorado as discussed by Super and Boe (1988). Airborne seeding with AgI was done upwind of the barrier during six experiments. The seeded cloud volume was followed by along-the-wind passes with the cloud physics aircraft as the seeding line passed over the mesa. An acoustical ice nucleus counter provided clear evidence of the seeded volume on most aircraft passes. Ice particle characteristics were compared from the seeded volumes to adjoining natural cloud. Very marked increases in IPC were observed following each seeding event. Frequent ice particle photography at the surface revealed the effects of seeding during the overhead passage of three of the seedlines. Two ground-based seeding experiments were reported that also resulted in substantial microphysical effects at aircraft altitudes. Light snowfall was observed to reach the mesa top from one of these experiments and surface snowfall was probably caused in the other. These experiments offer some of the most convincing physical evidence available that seeding winter orographic clouds can, under some conditions, result in precipitation increases at the surface.

**1.2.7 Sierra Nevada Experiments.** - Many attempts were made to conduct physical experiments during the course of the SCPP (Sierra Cooperative Pilot Project) in the Sierra Nevada of California (Reynolds and Dennis, 1986). A survey of 36 SCPP experiments is given by Deshler et al. (1990). A trajectory model was used to position the seeding aircraft so that resulting ice particles were calculated to settle on and around a well-instrumented target site well up the windward slope of the barrier. A cloud physics aircraft, weather radar, and aspirated ice particle imaging probe in the target were the primary means of documenting key links in the chain of physical events expected to follow seeding of the postfrontal stratus and stratocumulus clouds. The success rate for detecting seeding effects in the 36 experiments is stated as 35 percent for the aircraft, 4 percent for the radar, and 17 percent for the imaging probe on the surface. Only two cases were claimed to document all links in the chain of events resulting from seeding. The authors noted that, "A variety of reasons contributed to the poor success at measuring seeding effects." They pointed to factors such as the limited and variable SLW content of the clouds, the high natural IPC (due to ice multiplication) masking increased concentrations of ice particles due to seeding, and the logistics of coordinating the various measurement platforms which sometimes led to long delays in initiating seeding.

A more promising case study was recorded during the final SCPP field season (Deshler and Reynolds, 1990). A seedline of AgI was released by flying across the wind in a stratiform cloud with an acetone-fueled generator in operation. The research aircraft followed the seedline for over 90 minutes (100 km) with an acoustical ice nucleus counter, although passes between 19 and 61 minutes after seeding apparently were below the seedline. Enhanced IPC was associated with the seedline position from 64 to 90 minutes after seeding. Unfortunately, it was impractical to target the instrumented ground site and no indication of seeding effects was found in the precipitation gauge network.

**1.2.8 Tushar Range Experiments.** - Physical experiments were attempted on the Tushar Mountains of Utah during early 1989. Preliminary analysis of these experiments is discussed by Huggins and Sassen (1990). Silver-in-snow measurements suggest that the seeding material rarely reached the target. Examination of aspirated ice particle imaging probe data showed little success in demonstrating seeding effects at the intended target. The basic approach in the Tushar experiments was to operate one to three high-altitude AgI generators, basing targeting on upwind rawinsonde winds, in attempts to affect snowfall and cloud structure (revealed by radar, lidar and microwave radiometer) at and above the target. Generators were pulsed on and off at 1- to 2-hour intervals, and time changes in snowflake characteristics, precipitation rate, and snow silver content were expected to vary accordingly. In the absence of wind observations near the mountainous terrain, or aircraft tracking of the seeded volume, it seems unlikely that it will ever be determined where the AgI was transported.

**1.2.9 HIPLEX Summer Experiment.** - HIPLEX-1, while dealing with summer convective rather than winter orographic clouds, is worth noting because of the well-thought-out and detailed seeding hypothesis and well-designed field program, which monitored each key step in the physical hypothesis (Smith et al., 1984). The experiment failed to demonstrate statistically all hypothesized steps leading to rain on the ground. However, the reasons for the failure were apparent in the physical data set, which was a very important result (Cooper and Lawson, 1984). Yet another inconclusive statistical experiment might have resulted without the physical observations from every case.

## 1.3 Factors Affecting The Success Of Physical Experiments

It is worth trying to understand why marginal results were obtained from some past physical experiments, and impressive results were obtained from some others. Examples of the latter include the winter orographic seeding experiments conducted in the Cascade Project, the Bridger Range, and the Grand Mesa.

**1.3.1 Influence of Precipitation Intensity. -** A number of lessons became apparent in reviewing the various physical experiments cited. First, and not surprising, it is much simpler to document seeding effects leading to snowfall on the surface from nonprecipitating clouds than from those where nature is already somewhat efficient. The seeding signal can be unambiguous from clouds with a low IPC, as illustrated during the first three Grand Mesa seeding experiments of March 18, 1986 (Super and Boe, 1988). The only snow that fell throughout the period corresponded to passage of the seedlines. Also, their ground seeding experiment 2 days later produced the only snowfall anywhere on the Grand Mesa.

Nonprecipitating or lightly precipitating periods with SLW are common in Arizona winter storms. Radar, SLW, and precipitation rate observations over the Mogollon Rim indicated that the beginning and ending storm phases often had several hours with little natural snowfall and abundant SLW, and similar instances occurred during the middle of some storms (Super and Holroyd, 1989).

It is, of course, important to demonstrate whether seeding can produce physical evidence of enhanced snowfall when some natural snowfall is occurring but excess SLW still exists. Hobbs (1975a) showed evidence of snowfall increases during naturally light snowfall, and similar evidence at aircraft levels is given by Super and Heimbach (1988). It will likely be increasingly difficult to demonstrate that seeding enhances snowfall as natural precipitation rates increase. When nature becomes very efficient, seeding cannot increase the snowfall because all available SLW is already converted to ice. Fortunately, Arizona winter clouds tend to be either quite efficient or very inefficient (Super and Holroyd, 1989). This tendency may be common throughout the intermountain West. For example, Hobbs (1975b) indicated that clouds over the Cascades were generally in two categories, "those in which ice particle concentrations never exceeded 0.1 $L^{-1}$, and those in which the maximum concentrations were no less than about 10 $L^{-1}$ irrespective of temperature." It seems probable that analysis of individual well-designed physical experiments will show snowfall enhancement from naturally inefficient clouds, no enhancement from very efficient clouds, and only suggestive evidence of snowfall increases from moderately efficient clouds. However, grouping of several similar experiments should enhance the power of the analyses.

**1.3.2 Airborne Tracking of Seeded Volume. -** A very important factor common to successful physical experiments is airborne tracking of the seeded volume between the release point or line and the target area. The complexities of the three-dimensional airflow over mountains are sufficient to render suspect any windspeed and direction estimates based on upwind soundings and/or a few local surface measurements. It is almost essential that an aircraft monitor where the seeding material is going until it passes over the target, or is shown to have missed the target.

Some regions have serious airspace conflicts, for example, "victor" routes between major airports. Such high traffic areas should be avoided in planning experiments because needed airspace blocks will frequently be unavailable.

An even more serious consideration is to avoid mountain barriers that preclude flight near the surface. The usual restriction is that aircraft flying under IFR (instrument flight rules) must stay at least 600 m above the highest terrain within 8 km of the flight path. Special waivers can be obtained in some locations to allow flight within 300 m of the terrain, but nearby navigational aids are usually required. Even if the target is at a high elevation, still higher peaks nearby may preclude aircraft sampling within a kilometer or more above the target site. Yet a growing body of evidence shows that most of the SLW is concentrated in the lowest kilometer over the windward slope (e.g., Hobbs, 1975a; Holroyd and Super, 1984; Hill, 1986). Considerable ice particle growth can occur in this zone, so a 1-km vertical "gap" between lowest aircraft observations and the surface will cause considerable uncertainty concerning the growth, fallout, and targeting of ice particles resulting from seeding. The SCPP experiments, for example, suffered from both airspace conflicts and a rugged barrier making flight near the target site impractical. The latter condition was also a problem in the early 1989 experiments in the Tushar Mountains. The ideal mountain barrier for experimentation would allow surface sampling on the crestline, would have no higher peaks near the target site, would not have an abrupt crestline which could create serious downwind turbulence, and would have nearby navigational aids such as a VORTAC station. Fortunately, portions of the Mogollon Rim approximate the ideal except for a lack of nearby navigational aids.

**1.3.3 Direct Detection of Seeding Agent. -** Another requirement for physical experiments is that either the seeding material be detectable, or a tracer material be simultaneously released. Silver iodide can be tracked with an acoustical ice nucleus counter but dry ice is not traceable. Natural variations in IPC can easily mask the ice particles caused by seeding unless the seeding material itself, or a tracer material such as $SF_6$ gas, is independently measured to distinguish the seeded volume from natural cloud. In other words, attempting to specify the seeded volume by monitoring ice particles alone will lead to uncertain interpretation of seeding effects (Deshler and Reynolds, 1990).

A note of caution is in order in tracking either AgI or $SF_6$ with airborne detectors. Existing detection systems require a skilled operator who can recognize system malfunctions and correct them. A number of past attempts at airborne tracing failed because of improperly functioning equipment and/or insufficiently knowledgeable operators. These problems are rarely mentioned in project reports or publications and are only learned about through experience or personal communication. However, with properly maintained equipment, either AgI or $SF_6$ can be tracked for tens of kilometers under stable or neutral atmospheric lapse rates with reasonable release rates. For unstable conditions, required $SF_6$ release rates may become excessive, but AgI can readily be detected for long distances with an acoustical ice nucleus counter due to the vast quantity of potential ice nuclei produced. For example, Super et al. (1975) reported tracking an AgI plume from a single generator as far as 190 km downwind.

**1.3.4 Radar Detection. -** Radar has sometimes been used in attempts to follow the effects of seeding between lowest aircraft levels and surface instruments. However, radar evidence of winter orographic seeding effects is normally inconclusive unless the natural IPC is very low. That is because the radar reflectivity factor is not only directly proportional to particle concentration, but also proportional to the sum of the sixth powers of particle diameters. Thus, the returned signal from a few large natural snowflakes can completely mask that from thousands of smaller crystals produced by seeding. Seeding could conceivably decrease the radar signal while increasing the precipitation rate. Thus, radar is not suitable for detecting seeding effects except in special cases such as reported by Hobbs et al. (1981). However, radar scanning can be very valuable in monitoring natural variations in cloud structure over the entire region of the target. Such variations can mask, or be mistaken for, real seeding signatures and it is important that they be documented.

Doppler radar sets can provide important wind measurements over the experimental area in addition to reflectivity data. The wind data can help interpret the reflectivity patterns.

**1.3.5 Precipitation Characteristics. -** The most detectable effect of seeding at ground level is usually an increase in the IPC. Changes in ice crystal sizes and habits, and silver content in the snow, also suggest that seeding affected the precipitation process. However, successful seeding usually increases the concentration of ice crystals to levels well above background. Much of the IPC enhancement will likely be at small crystal sizes, less than a millimeter in diameter. Small crystals produced by seeding are often in the form of hexagonal plates. An aspirated particle imaging probe offers the most practical means of continuously monitoring ice crystal characteristics. However, it should be supplemented by photographic documentation which provides more detailed data, though requiring considerable manual reduction.

The riming process (also called accretional growth) is the freezing of tiny cloud droplets to the falling ice crystals. It was shown to have been reduced in some of the reviewed experiments. This should be a consequence of seeding if enough ice crystals are created to utilize most of the excess SLW. The degree of riming usually is not discernible from aspirated imaging probe data so manual or photographic observations are required at the surface target.

Obtaining snow samples for silver analysis at frequent intervals is useful in evaluation of seeding effectiveness. Enhanced silver levels in the snow do not prove any seeding effect directly since most or all of the silver could result from scavenging by natural snowflakes. However, finding only background silver concentrations very likely means the target was not impacted by seeding. Thus, the silver-in-snow data provide a check against claiming natural variations as seeding effects.

Highly sensitive precipitation gauges are needed for physical experiments because the seeding effects may be very brief (e.g., only a fraction of an hour for a single seedline laid down by an airplane), and precipitation rates may be low. For example, the total precipitation amounts from individual seedlines of AgI reported by Super and Boe (1988) ranged from 0.10 to 0.22 mm water equivalent. Conventional weighing gauges have a resolution of 0.25 mm, and are unsuitable for physical experiments unless modified.

**1.3.6 General Considerations. -** Some of the reviewed studies attempted to "piggy-back" physical experiments on experiments designed for statistical evaluation. This approach was generally unsatisfactory. Most statistical experiments attempt to affect a sizable area for a significant time requiring seeding of a relatively large volume of atmosphere, for example, the release of several seedlines for airborne seeding. Such seeding takes substantial time. Yet, one of the main approaches for analyzing physical experiments is to examine temporal changes in expected characteristics (IPC, precipitation rate, degree of riming, etc.). This is best done by reducing the time required for seeding, say to a single seedline for airborne seeding, thus reducing the effect of natural changes in the constantly varying atmosphere during the course of the experiment.

Even with a single seedline, natural variability can mask seeding effects. It is very important to monitor both the temporal and spatial changes over and near a the target site. One useful approach is to operate surface measurement stations in addition to the target. These stations should be located crosswind of the area expected to be affected by seeding so as to provide a record of natural variations. Radar observations of the region can also be very helpful in this regard, as noted earlier. It is essential that enough observations be collected in both space and time to determine which perturbations are real seeding effects, which are natural variations, and which may be seeding effects masked by natural variations.

Some past weather modification experiments seriously underestimated the resources required to analyze their field observations, or delayed detailed analysis until several field seasons were completed. In either case the very valuable feedback from analysis to improving field design was lost. In the worst case, programs were canceled after several years of expensive data collection, but before adequate analysis and reporting. Such programs were very wasteful of time and resources. It is strongly recommended that the Arizona Program provide substantial funding for analysis, and that analyses of each field season's data be reasonably complete before finalization of the next season's design. Conducting field expeditions every second or third year is one approach to accomplishing this. Another is to isolate the analyses group from any field involvement beyond that required for their familiarity of general field techniques and procedures. In general, it is preferred to have the same scientists collect and analyze the data. This ensures careful collection and, even more important, expands the scientists' comprehension of the overall project, which can significantly improve both design and analysis. However, use of the same group in both roles does require considerably more time for completion of the experimental program.

Any physical experiment requires some targeting scheme to decide when and where to release the seeding material in the case of a fixed target, or when and where to operate the "mobile target" (usually sampling aircraft) in the case of fixed generator locations. The scheme may be no more complicated than using a typical wind velocity for the altitude range in question to estimate transport time, and typical growth rates and fall speeds for the type(s) of ice particles expected. Such approaches are sometimes referred to as "back of the envelope" calculations. On the other extreme, a highly sophisticated three-dimensional time-dependent numerical model may be run on a supercomputer to simulate the entire airflow pattern around the barrier and all important microphysical processes for expected ranges of conditions. Given the uncertainties in certain key processes (e.g., aggregational growth rates) and impracticality of making detailed measurements around mountains, in particular concerning the winds and the spatial distribution of SLW, it is probably more reasonable to use a targeting model of modest sophistication that can be run on a small computer in the field using real-time input data. The approach used by Rauber et al. (1988) for the SCPP is a good compromise. If resources permit, a more sophisticated model should be run for various combinations of atmospheric conditions believed typical of winter storms in the region of interest. The resulting predictions should be in general agreement with the operationally used scheme or the latter might require some modification. For the purposes of the Arizona Program, it is advised that an existing numerical model of moderate sophistication be adapted for the Mogollon Rim, compared with real observations, and modified if necessary for real-time decision making during physical experiments. Because of the uncertainties mentioned, any model should only be used for general guidance as its predictions are no substitute for actual measurements of reality.

An important lesson concerning physical cloud seeding experiments is that they should be as complex as required to document and understand the important phenomena, *but no more so.*

Experiments frequently have attempted to meet too many goals for the resources and number of storms available with the result that none were well met. Side issues have a way of evolving into key issues to the detriment of those few questions that are critically important to answer. The goal of the physical experiments discussed in this report is to develop a *demonstrated* ability to seed some Arizona winter orographic clouds in a manner leading to enhanced snowfall on the Mogollon Rim. It is not to improve weather forecasting, develop some new type of instrument (unless critical to the experiments), pursue some interesting but nonessential basic research or to provide topics for theses. Some past experimental projects have allowed such "hidden agendas" to compete for limited resources. The end result has been progress at a much slower rate than possible, so that policy makers have grown weary of waiting for clear indications of an authenticated, useful technology.

The history of scientific weather modification has clearly shown that they are no quick answers and no easy way to success. However, persistence in pursuing the *critical* uncertainties will lead to significant improvements in the emerging technology. Both scientists and policy makers need to be continually reminded that scientific progress, while rarely rapid, will be extremely slow if attention does not remain focused on the key uncertainties.

## 1.4 Optimum Area for Arizona Physical Seeding Experiments

**1.4.1 Search for the Optimum Area.** - Topography, air traffic restrictions, surface access, and prior Reclamation field experience were all considered for the entire Mogollon Rim higher than 1830 m[1] from the San Francisco Peaks just north of Flagstaff to the White Mountains bordering New Mexico. It is considered impractical to use separate research areas for ground-based and airborne seeding, as similar extensive ground instrumentation is required in either case. Moreover, it is desirable to be able to shift from one seeding mode to the other as storm conditions change.

The search for the best area for physical experiments soon focused on the region south of Flagstaff (fig. 1.1). The high elevation region from about Mormon Lake to the intersection of state highway No. 87 and the road that passes southward from Mormon Lake (Forest Service Road No. 3, also called Lake Mary Road) appeared to have particular advantages for experimentation. The portion of the Mogollon Rim from Mormon Lake to about 45 km south-southeast, referred to as the Happy Jack area, was chosen as most feasible, largely by a process of elimination as will be described.

In-cloud aircraft seeding and sampling over the high country north of Mormon Lake would experience conflicts with air traffic control for the Flagstaff Airport, and would have to stay above the very high San Francisco Peaks when north of Flagstaff. The portion of the Mogollon Rim immediately north through east from Payson would be impractical because it is under a major air traffic route for the Phoenix airport and airspace conflicts would be common above 3350 m. Further, high elevation surface access would be difficult in that region because of the absence of all-weather roads. The White Mountains, which extend into New Mexico (not shown on fig. 1.1), have limited all-weather surface access and none to the higher elevations west of the town of Alpine. Moreover, air traffic conflicts would often exist because of MOAs (military operating areas). The Williams 3 MOA is immediately west of the White Mountains and the Reserve MOA is over the southeast quadrant of these mountains. Elevations in the vicinity of Pinedale and Show Low are lower than the rest of the rim so uplift, condensate production and, hence, seeding

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[1] All elevations are above sea level.

opportunities would likely be reduced. The remaining area of the rim is the vicinity of Happy Jack, located 20 km south of Mormon Lake, where Reclamation conducted a field program in early 1987. As discussed by Super et al. (1989), flight restrictions are minimal in that area. An all-weather road passes through the region (Lake Mary Road), generally along the crestline of the rim, which would provide practical access for project personnel and equipment.

Based on the considerations above, the region around Mormon Lake and Happy Jack is proposed as the most suitable for experimentation.

**1.4.2 Aircraft Sampling Over the Selected Experimental Area.** - Normal IFR flight procedures established by the FAA (Federal Aviation Administration) require aircraft to stay at least 600 m above the highest terrain within 8 km of the flight path. Special waivers may be obtained in certain circumstances for reduced separation; for example, only 300 m separation and a 3-km horizontal separation were required for a specific flight path over the valley upwind of the Tushar Mountains in early 1989 (Utah, 1989). Such special waivers require permission by the FAA and can be sought only when the specific terrain, aircraft, navigational aids, and pilots in question have been established. However, discussions with FAA personnel in the Scottsdale Flight Standards District Office suggested that a waver for flight within 300 m of the highest terrain within 3 km of the flight path may be obtainable for the region of interest, especially if navigational aids are upgraded (e.g., improved Loran-C coverage, addition of a nondirectional beacon). For the purpose of this design document it will be assumed that such a waiver will be obtained.

A more detailed examination of the Happy Jack region indicated that two minor peaks would most interfere with low-level aircraft sampling. These are Mormon Mountain immediately northwest of Mormon Lake, which has a tower rising to 2666 m, and Hutch Mountain at 2601 m located 18.5 km southeast of Mormon Mountain. In practice, when calculating minimum terrain clearance for aviation, the highest ground elevation is rounded up to the next 30-m contour. For the higher of the two peaks, this results in a minimum flight altitude of 2990 m.

The general airflow during SLW periods over the Happy Jack area is known to be from the southwest with a secondary maximum from the northeast [fig. 5-5 of Super et al. (1989)]. Therefore, it would be practical to fly along-the-wind passes lower than 2990 m by staying at least 3 km crosswind of these two peaks, that is, along a 12-km-wide corridor centered between them. Flight along a southwest-northeast path would be practical down to about 2800 m in this corridor. Crosswind passes would have to stay above 2990 m when over the crestline of the rim, but could descend as terrain elevation decreases to the southwest or northeast. Surface observations could readily be made near 2270 m within the corridor, or 530 m below the lowest flight altitude. The only alternative for lower flight over this portion of the rim would be to fly along-the-wind passes at least 6 km southeast of Hutch Mountain. However, that region is atypical because the terrain rapidly decreases in elevation towards the south.

**1.4.3 Ground Survey for a Target Site.** - The region between Mormon Lake and Happy Jack was extensively surveyed on the ground during September 1989. The limited number of existing large clearings within about 2 km of the highway were examined for suitability as the well-instrumented target site. Factors considered included clearing size, orientation and slope, proximity to existing roads and powerlines, stability of the surface for bearing instrumentation systems (many of the clearings become shallow lakes during snowmelt periods), and nearby small sheltered clearings for ice particle and precipitation observations. It was also considered desirable to locate the target within the Verde River Drainage. The best overall site was determined to be near Allen Lake Tank (hereafter called Allen Lake), located midway between the town of Mormon Lake and Happy Jack at an elevation of 2270 m, longitude of 111° 26' 24", latitude of 34° 49' 27". The site is far enough from Hutch Mountain to permit overhead aircraft sampling down to 2800 m, or 530 m a.g.l. It is near a powerline and the highway, and is large enough to permit tipping curve calibrations of a microwave radiometer and operation of a Doppler acoustic sounder. The clearing is in the Verde River Drainage, within a kilometer of the crestline of the Mogollon Rim. The most serious drawback is the lack of nearby dense forest for ice particle and precipitation measurements. Snowfences may be required in addition to the existing tree cover to minimize wind effects on these observations.

## 1.5 Observing Systems for Physical Experiments

**1.5.1 Scientific Uncertainties.** - In the case of Arizona winter clouds, scientific uncertainties were substantially reduced during the early 1987 and early 1988 field programs as discussed by Super et al. (1989). Most important, it was shown that abundant excess SLW existed during portions of most synoptic-scale winter storms, particularly during the beginning and ending phases and at other times when clouds were shallow so the IPC was limited. Flow perpendicular to the barrier, usually south-southwesterly but sometimes the reciprocal, was responsible for the uplift that produced most of the SLW. The bulk of the SLW appeared to be near the surface, where maximum uplift and water vapor content should combine into greatest condensate. The SLW at aircraft levels was usually limited.

Ground releases of tracer gas showed that it usually dispersed through the lowest several hundred meters of the atmosphere with typical neutral stabilities, but that this layer would often be too warm for significant ice formation by conventional types of AgI.

Ice multiplication was not frequent in Arizona winter clouds, at least at aircraft sampling levels, contrary to findings over the Sierra Nevada where cloud seeding potential was markedly reduced by the naturally abundant IPC. High IPC frequently existed in the Arizona clouds, but usually as a result of high, cold clouds and presumably primary ice nucleation.

In spite of the progress made in the first two field programs, a number of uncertainties remain. Key questions to be addressed include:

1. What is the SLW distribution upwind of the barrier? How frequently does SLW extend far enough upwind, and at a cold enough temperature, for ice particles created by seeding to have the opportunity to grow and fall on the upwind side of the barrier?

2. How rapidly will seeding-produced crystals grow and fall to the surface? Not only the SLW distribution and its temperature influence crystal growth and fallout. Ice particle fall speeds are reasonably well known in still air, but vertical motions in excess of crystal fall speeds are common near mountain barriers. For stable and neutral conditions these may be approximated by the slope of the barrier multiplied by the horizontal wind component normal to the barrier. However, embedded convection can significantly enhance vertical speeds. Even more important are the ice crystal growth mechanisms involved. Diffusional growth is reasonably well documented, at least for several minutes following nucleation. Accretional growth is less understood and aggregational growth is poorly understood. Yet the latter is likely when large concentrations of dendritic crystals or needles are formed by seeding.

3. Do conditions exist such that seeding will reduce the snowfall on the Mogollon Rim? There is conflicting evidence on this point and more physical evidence is needed to test limited statistical suggestions that such decreases can be significant. The reality and magnitude of any seeding-caused decreases should be known prior to implementation of operational seeding.

4. How frequently can ground-released AgI result in significant concentrations of ice crystals well upwind of the barrier to allow for crystal growth and fallout?

5. Does nature enhance the IPC near the ground? Super et al. (1989) discuss large apparent increases in IPC between lowest aircraft sampling levels and the ground. Because of differences in sampling times between the aircraft and ground systems, and artificial increases due to snowflake breakup in the ground probe, it could not be determined how much of the apparent increase was real. However, low-level ice crystal development has been observed at other mountain barriers, possibly because transient supersaturations in the ascending air allow natural ice nuclei to become effective. The amount of natural ice particle formation in the lowest several hundred meters above the Mogollon Rim needs to be documented, as any such formation would be competing with seeding caused crystals for the available SLW.

These uncertainties all suggest caution should be exercised in using numerical model predictions. Model outputs should certainly be used for general guidance in conducting seeding experiments. Models will no doubt improve as better observational evidence becomes available and leads to more through theoretical understanding. However, at this stage an empirical approach continues to be required, with the effect of seeding under particular conditions demonstrated by comprehensive physical observations.

**1.5.2 General Overview.** - A number of sophisticated observational systems are required for detection of key physical processes in comprehensive physical seeding experiments, whether ground-based or airborne seeding is used. Additional measurement systems will provide supporting data to assist in conduct of experiments and post hoc analysis of the resulting data base. A specially instrumented aircraft, hereafter called the cloud physics aircraft, will be the primary airborne sensing platform. Ground observing systems will include a scanning Doppler radar; a microwave radiometer; a Doppler acoustic sounder; an aspirated ice particle imaging probe; a laser ceilometer; tower-mounted wind, temperature, humidity, and icing sensors; and a network of high-resolution precipitation gauges. In addition, manual observations will include frequent sampling of surface snowfall for precipitation rate and later silver content analysis, and microphotographs of ice crystals to reveal details of structure and evidence of riming growth. These systems will now be described, and brief discussion given of their respective roles in the experiments. The instrumentation required on the cloud physics and seeding aircraft will be described first, followed by the ground-based measurement systems. Sections 1.6 and 1.7 will provide more detail on how the various observing systems will be integrated in conduct of the ground-based and aircraft seeding experiments, respectively.

**1.5.3 Cloud Physics Aircraft.** - The most valuable cloud physics aircraft measurements will be SLW, IPC, and AgI concentration, all referenced to position and time. King and J-W hot wire probes and a PMS-FSSP sensor (see the appendix for listing of instrument sources) will be used to monitor SLW, which must be present for seeding to create significant concentrations of ice particles. The FSSP also yields cloud droplet concentrations and sizes, of special interest concerning possible ice multiplication (Hallet and Mossop, 1974). A PMS 2D-C particle imaging probe will provide IPC and particle sizes and an estimation of habits. If SLW is present, the seeded cloud volume should have markedly greater IPC than would natural cloud. Much of the IPC increase can be expected to consist of relatively small newly formed crystals, with habits appropriate for the sampling-level temperature. An acoustical ice nucleus counter (Langer, 1973) will be used to measure AgI concentrations and detect the approximate boundaries of the AgI plume or seedline by the method of Super et al. (1988).

While not essential, a PMS 2D-P probe would be valuable for monitoring snowflakes larger than about a millimeter in diameter. The 2D-C probe has limitations in observing these larger particles which exist in much lower concentrations than do the small ice crystals. Yet most of the precipitation mass is contained in the larger particles.

Other cloud physics aircraft instrumentation will include sensors for monitoring pressure altitude, horizontal position, temperature, dew-point temperature, indicated airspeed, and heading. Horizontal wind velocity will be calculated from heading, true airspeed, and position. A radar altimeter will indicate terrain clearance. A forward-looking video camera will document cloud structure. Both graphic and text displays of current and recent observations will be available to the aircraft scientist to aid in conduct of the mission (experiment). The scientist and other crew members (pilot and data system operator) will have intercom communication plus radio communication with project personnel on the ground.

**1.5.4 Seeding Aircraft.** - The seeding aircraft will carry an Aero Systems Model E-16 generator, which uses compressed gas to pressurize a solution of AgI-in-acetone. The solution flows through a nozzle, where it is atomized, into the burning chamber, where the acetone is burned and the AgI vaporized. In the exhaust region, the AgI crystallizes, producing high concentrations of tiny AgI particles. Since no other fuel is used, monitoring the temperature in the burning chamber provides sure evidence of whether the generator is on or off.

The seeding aircraft also will have limited instrumentation consisting of time-referenced recordings of J-W liquid water content, air temperature, dew-point temperature, pressure altitude, horizontal position, heading, indicated airspeed and AgI generator temperature. Approximate horizontal wind velocity will be calculated from the heading, airspeed, and position information. A forward-looking video camera will document general cloud conditions over the experimental area. The seeding aircraft will be equipped to release radar chaff several times during each mission in order to mark the locations of seeding agent release. Only the pilot will fly on this aircraft which, like the cloud physics plane, must be equipped for flight into known icing conditions.

Both aircraft will use state-of-the-art Loran-C receivers for primary in-cloud navigation. A flight test in September 1989 indicated that conventional VOR-DME equipment would not receive signals from the Flagstaff and Winslow VORTAC stations within 300 m elevation of the highest terrain in the experimental area. Other navigational alternatives are much more expensive. The Mogollon Rim is presently in the "mid-continent gap" for Loran-C, but new stations scheduled for installation during 1991 should eliminate this problem. Moreover, recently marketed receivers can triangulate from more than one Loran chain.

**1.5.5 Project Operations Center.** - A scanning Doppler radar, sensitive enough to observe very light snowfall (-10 dBz) at 5-km range, will be located at the operations center above the northeast shore of Mormon Lake in the largest clearing on the heavily forested crestline area. The site is the only clearing large enough to allow the radar antenna to be tilted to low elevation angles without blockage by terrain or trees. This will permit near-surface scanning through seeded volumes over the Allen Lake region, as well as through adjoining natural cloud. Mormon Mountain will block scanning north of a line running west-southwest from the radar, but airflow is rarely from the west or northwest during storms (Super et al., 1989). Sector scanning will be used through a range of elevation angles over the region of interest to provide observations of cloud tops and structure. An antenna beam width in the range of 1.0° to 1.6° will enable reasonable spatial resolution over the target region. Periodic wind measurements will result from tracking aircraft-released radar chaff. These wind observations will help evaluate targeting for the seeding experiments. The Doppler capability will permit real-time display of the wind component toward and away from the radar which should be representative of the wind over Allen Lake. The Doppler information will be especially valuable in postseason analysis of the experiments.

At least some of the observations from each of the below noted Allen Lake systems, and some from other project locations, will be routinely transmitted to the Mormon Lake radar site which will be the project operations center. Satellite photos, weather maps and other forecast products also will be received there by satellite downlink. The FC (field coordinator), with the project forecaster's assistance, will use this information in deciding when and how to conduct experiments and what type they should be. For example, SLW must be present for seeding to have any substantial effect. The low-level winds must be from the general direction of the generators to affect the target area with ground seeding. Wind observations and targeting model predictions will be used to direct the seeding aircraft where to release AgI. Seeding would not be initiated if the radar revealed marked changes in the approaching cloud structure which would mask seeding effects.

The primary reason for colocating the project operations center and the radar is that in order to coordinate experiments the FC needs real-time visual access to the patterns of reflectivity factor and Doppler winds. The needed information is portrayed on the radar "scopes" (cathode ray tubes), but it would be quite difficult to transmit that much data elsewhere in real-time. In contrast, other information needed by the FC readily can be transmitted to the radar.

**1.5.6 Target Site.** - The Allen Lake target site will have several instruments. A microwave radiometer will be operated there in the vertically pointed mode to monitor whether excess SLW is passing overhead. Hogg et al. (1983) discuss the theory and use of radiometers for monitoring integrated water vapor and liquid water amounts along their field of view. A Doppler acoustic sounder will monitor winds in the lowest kilometer above ground to aid in targeting assessment. A tower will be erected near the radiometer and equipped with sensors for wind velocity, temperature, humidity, and icing measurements well above treetop levels. The tower will also have a nondirectional radio beacon to assist in aircraft navigation. An acoustical ice nucleus counter will be operated to detect whether AgI is being transported to the site. This will have particular importance with ground seeding when the AgI plume should impact the surface. Aircraft-released AgI also may be detected if it is carried to the surface by precipitation and released, possibly by sublimation of tiny crystals. A laser ceilometer will be operated to monitor the cloud base above the rim. This measurement will likely coincide with the lower boundary of the SLW when it is present. Ice particles can be expected to continue growing until they fall below the liquid cloud.

An aspirated ice particle imaging probe (PMS 2D-C) (Humphries, 1985) will be operated in a sheltered location in the forest near Allen Lake to estimate IPC, crystal sizes, and types. It will provide minute-by-minute observations. Very high-resolution precipitation rate observations will be made nearby. An accurate balance or load cell will be used to weigh precipitation amounts falling on the surface. Microphotographs of ice particles will taken for documentation of accretional growth, and for more accurate classification of ice crystals than is possible with the 2D-C imaging probe.

Snow will be collected at the ground for later silver analysis. Finding silver levels above the natural background does not prove that seeding enhanced the snowfall, because scavenging by natural snowflakes can also bring AgI to the surface. However, failure to detect increased silver indicates unsuccessful targeting. Thus, silver-in-snow measurements will sharpen delineation of seeded and nonseeded periods.

Surface temperatures are often near freezing during snowfall on the experimental area. The resulting snowmelt makes identification of ice crystal types difficult, and can interfere with silver content sampling as the snow samples should be kept frozen until analysis. It is planned to construct a small refrigerated shelter near Allen Lake to be kept below freezing. Snow samples will be collected below openings in the roof.

**1.5.7 Precipitation Observations.** - A total of about 12 high-resolution precipitation gauges located located approximately 3 km apart along Lake Mary and Stoneman Lake Roads (see fig. 1.2), and near a trail which extends eastward from the southeast corner of Mormon Lake. The purpose of the gauge network will be to monitor precipitation rates and accumulations to be used in analysis of seeding effects. Enhanced precipitation at the surface is the desired final link in the chain of physical events following seeding. Consequently, the importance of adequate precipitation measurements cannot be overemphasized and substantial effort must be made to insure that such observations are reliably and accurately made. The Allen Lake target is particularly important, but observations from surrounding sites will greatly enhance demonstration of the area affected by seeding and the precipitation magnitudes involved. Radar may assist in delineation of the area of snowfall enhancement under some conditions, generally when natural snowfall in very light or nil. The precipitation gauge network will provide the only surface evidence of seeding effectiveness beyond the Allen Lake target, and a secondary target site used during some airborne seeding experiments (see secs. 1.5.7 and 1.7.5).

High-resolution precipitation observations are needed for physical seeding experiments as shown by Super and Boe (1988) and the review by Reynolds (1988). The gauges must be able to resolve 0.1 mm or less water equivalent, and have a time resolution of 15 minutes of less. Conventional Belfort weighing gauge mechanisms may be used, with 45.4-cm-diameter orifices that provide five times the catch area of the standard 20.3-cm-diameter gauge. Manufacturer's specifications claim a resolution of 0.25 mm with standard orifices so the modified gauges should provide 0.05-mm resolution. These large orifices gauges, successfully used on the Grand Mesa of Colorado (Super and Boe, 1988), also eliminate catch errors due to snowfall "capping" over the gauge openings. However, increasing the catch area reduces the gauge capacity (to about a 45-mm accumulation with a 45.4-cm orifice) so that frequent servicing is necessary. Recent developments in load cell gauges should be reviewed shortly before gauge procurement, as they could offer advantages in servicing frequency and data handling if temperature effects can be dealt with.

For the purpose of minimizing wind-induced catch errors, each gauge will be located in a well-protected clearing in the forest, and will be equipped with an Alter-type windshield. It is well documented that even light winds can substantially reduce gauge catch as compared to actual snowfall on the surface. All gauges will be located near roads to make frequent servicing practical, as is necessary with gauges of high-resolution but limited capacity. Off-road travel is sometimes very difficult in the experimental area due to frequent mid-winter snowmelt periods.

Since the AgI plumes resulting from either ground or orbiting aircraft releases will be monitored by aircraft, the gauges likely affected by the seeding can be estimated for each experiment. Precipitation amounts from these "target" gauges will be compared with nearby "control" gauges expected to receive only natural snowfall. The cloud physics aircraft will also monitor the positions of aircraft-released lines of AgI and associated ice particles. The passage of these across-the-wind seedlines should be evident in the time histories of precipitation across the gauge network when seeding produces detectable snowfall.

**1.5.8 Additional Ground Systems.** - An additional monitoring station will be operated to obtain manually very high-resolution precipitation measurements, snow accumulations for silver analysis and microphotographs, similar to the Allen Lake manual observations. These data will be collected for each experiment at one of two protected clearings in the forest. During seeding experiments that release an along-the-wind plume of AgI (secs. 1.6 and 1.7), a site about 20 km south of Allen Lake will provide crosswind, nonseeded control observations. During aircraft releases of crosswind seedlines of AgI, monitoring will take place about 5 km north of Allen Lake to provide a second set of high-resolution measurements in the area expected to be affected by seeding. Both clearings will have a small refrigerated shelter to facilitate snow sampling when surface temperatures are near 0 °C.

An automated weather station will be maintained near the Crooks Trail Road seeding generator locations to provide near-surface observations of windspeed, wind direction, and temperature. These data and derived statistics may be transmitted to the project operations center to assist in real-time decisions concerning missions. The measurements also will be used for post hoc analysis of the physical seeding experiments.

Two rawinsonde sites will be operated during experiments, one at Allen Lake and the other near Camp Verde about 45 km southwest of Allen Lake (in addition, the NWS takes soundings at 0500 and 1700 m.s.t. each day at Winslow, 70 km east-northeast of Allen Lake). Releases will be made at about 2-hour intervals, starting when the decision is made to commence an experiment, and continuing until completion of the mission. These soundings of wind, temperature, moisture, and pressure will be used as input for a targeting model to predict where to release AgI so as to affect the target. The upper air observations also will be valuable in post hoc analysis of each experiment.

The Camp Verde rawinsonde site will be equipped with a video camera to take time-lapse photos of the cloud cover over the general target area during daylight periods. These will be useful in post hoc analysis of cloud type, evolution, and structure.

It would be highly desirable to operate a second radiometer several kilometers southwest of the crestline, or in a mobile mode along Stoneman Lake Road, to improve information on the upwind extent of the SLW. Delineation of the SLW zone's position upwind and over the Mogollon Rim is very important in evaluation of seeding potential. Ice crystal growth is very dependent upon the amount of SLW present and its extent along the crystal trajectories. Numerical models used to calculate ice particle growth and fallout must estimate where the SLW exists and in what amounts, but these estimates need confirmation by actual observations. At present, knowledge concerning SLW fields over mountain barriers is limited because of the difficulties of observation.
A second radiometer could significantly assist in improving this knowledge of SLW over the experimental area. It could make RHI (range-height indicator) scans in the vertical plane along the wind. Such scans would provide observations directly overhead and also along slant angles upwind and downwind of the radiometer. Radiometer data can be difficult to interpret since no

information is provided about where SLW exists along the beam. However, important inferences are possible, especially when other information is available (e.g., aircraft observations).

## 1.6 Ground-Based Seeding Experiments

**1.6.1 Conceptual Model of Seeding Winter Orographic Clouds.** - Both ground-based and aircraft seeding experiments will be based on a hypothesis of the physical processes that take place when AgI ice nuclei are released in an attempt to alter the microphysics of winter mountain clouds. The conceptual model of what should happen following seeding of a winter orographic cloud has not changed markedly since Ludlam (1955) wrote his classic article on the subject. Similar ideas were expressed in different form by Super and Heimbach (1983) in discussing what general statements could be made about artificial seeding. They stated that,

> "In order for cloud seeding to increase snowfall from winter clouds over mountainous terrain, several links in a physical chain of events must exist. First, seeding material must be successfully and reliably produced. Second, this material must be transported into a region of cloud that has supercooled water or ice supersaturation in excess of that which can be converted to ice by naturally produced ice crystals. Third, the seeding material must have dispersed sufficiently upon reaching this region so that a significant volume is affected by the desired concentration range of ice nuclei or the resulting ice crystals. In the case of silver iodide (AgI) seeding this requires, fourth, that the temperature be low enough for substantial nucleation to occur. Once ice crystals form, they must remain in an environment suitable for growth long enough to enable fallout to occur, generally prior to their being carried beyond the mountain barrier where downslope motion, cloud evaporation and ice crystal sublimation typically exist."

This general conceptual model will be refined by the results of the physical seeding experiments into a detailed seeding hypothesis for later experimentation. Numerical modeling efforts will also assist in developing a detailed hypothesis.

**1.6.2 General Approaches.** - There are two basic approaches when attempting to detect the effects of ground-based seeding at the surface - either (1) fix the target location and move the generator(s) about for each experiment, or (2) fix the generator(s) and calculate the spot that will be affected (the target). Generally, it is more practical to establish a well-instrumented surface target and operate a number of generators spaced across the wind to reduce the probability of missing the target due to minor wind shifts and terrain-induced perturbations in the airflow. Some thought was given to using a fixed generator and moving the target by transporting instruments on a truck. For example, an ice particle imaging probe could be driven along the Lake Mary Road. However, a tall pine forest exists very near most of the highway, and snow blowing off the trees would likely interfere with any measurements made along the road. Accordingly, a single well-instrumented target site will be operated near Allen Lake.

**1.6.3 Temperature Limitation to AgI Effectiveness.** - As discussed in the T&D (transport and diffusion) studies reported by Super et al. (1989), there is serious doubt that ground-released AgI will routinely disperse to a sufficiently high and cold level in Arizona winter clouds for significant nucleation of ice crystals. This problem exists for a large fraction of storms even in more northern (colder) climates with higher terrain as noted by Super and Heimbach (1983) and Holroyd et al. (1988). Simulations using a tracer gas over the Mogollon Rim in 1987 indicated that most of the lowest kilometer above ground would contain the seeding agent, but that conventional types of AgI would affect only the coldest storms in this zone because of AgI's strong temperature dependence as an effective ice nucleus. Should further research indicate that only a small fraction of the Arizona storms are seedable with ground generators, the ground-based option would likely be abandoned. However, the 1987 simulations were based on cloud chamber results. The effective AgI ice nuclei output for real clouds may be higher as suggested by Deshler and Reynolds (1990). Further, some recently developed types of AgI show promise of improved nucleation at warm temperatures.

Airborne seeding and associated aircraft sampling will also indicate the temperature at which AgI nucleation in significant concentrations is achievable in real clouds. However, it is still important to conduct ground seeding experiments, especially during periods with embedded convection. These frequently occurring storm conditions were not sampled during the early 1987 T&D experiments. Since embedded convection is expected to enhance vertical mixing to higher, colder levels, it is important to determine whether ground-based seeding can be effective during such periods. This determination can best be done through ground-based physical seeding experiments.

**1.6.4 Ground-Seeding Considerations. -** The ground-based seeding during the first field season will use three portable high output generators, spaced about 3 km apart, to enhance the probability of proper targeting. Individual AgI plumes from the three generators should merge into a single plume, usually wider than 10 km, before reaching the target. A generator will be chosen that has been shown to have a high efficiency at warm temperatures in cloud simulation laboratory tests, and is also practical for field use. It will burn an AgI-in-acetone solution in a propane flame. One of the recently developed types of AgI which appears to be fast functioning and particularly effective at warm temperatures will be used in the generator. Further discussion concerning seeding agents is given in section 1.7. The generators will be transported by truck, and usually will be operated from positions along the Crooks Trail Road. Those portions of the road above 1800 m are suitable for transport of AgI toward Allen Lake with south to southwest winds (fig. 1.2). Three T&D experiments during early 1987 used a release point on this road and each time the tracer gas plume passed over or slightly north of the intended Happy Jack target. A network of remote AgI generators would be required for targeting with a wider range of wind directions. Such a network will be established only if the results of the initial field season justify it.

Ground generator-to-target distances will be about 35 to 45 km from Crooks Trail Road to Allen Lake, with corresponding travel times of approximately 1 hour for typical windspeeds. This should allow adequate time for dispersion of the seeding material, and for growth and fallout of ice crystals, provided that SLW extends well upwind of the crestline at temperatures cold enough for ice nucleation.

Some ground seeding will be done from 2000 m elevation on Tule Mesa in the Black Hills west of the Verde River. This would increase the release point to target distance by 22 km (travel time by about 0.5 h) for southwest flow, which might significantly enhance the vertical mixing. A number of high points along the Black Hills could be used for future ground releases of AgI, so their suitability should be investigated.

Ground-based seeding experiments usually will be initiated when some SLW exists over the target, surface temperatures are cold enough for a reasonable chance of AgI nucleation of ice within the lowest kilometer above ground, and wind observations indicate that the AgI should be transported from available seeding sites over the target. The presence of embedded convection also could be helpful, in enhancement of vertical dispersion of the seeding agent. However, some ground-based seeding experiments will be conducted during precipitating periods with suitable winds and temperatures for AgI nucleation, but little or no SLW present. It is expected that such seeding will not result in observable microphysical changes in the clouds (as found by Super and Heimbach, 1988, during all-ice cloud periods), or on the ground. However, it is important to demonstrate that seeding does not decrease snowfall during naturally efficient snowfall periods.

**1.6.5 Aircraft Sampling.** - The cloud physics aircraft will be the primary system for detection of the seeding plume although radar observations and measurements at the target site may also indicate its position. Personnel in the aircraft, the project operations center, and at the Allen Lake ground target will be in radio contact, so AgI plume position and other information will be communicated. If the seeding plume is not over the target, the portable ground generators may be moved to correct the targeting.

The cloud physics aircraft repeatedly will make crosswind passes through and beyond the seeding plume so that nonseeded cloud and precipitation can be compared with the seeded zone. Plume sampling passes will commence with a pair of passes as close to the ground as practical and about 20 km upwind of Allen Lake. This pair of passes, flown in opposite directions to permit AgI plume edge estimates with the acoustical counter (see Super et al., 1988), will establish the general direction of transport of the seeding material.

After proper targeting is established, the cloud physics aircraft will make its first series of vertically stepped passes about 10 km upwind of the target and approximately normal to the prevailing wind. This should sample some of the ice particles that will settle upon the target, given typical windspeeds and crystal fall velocities. The aircraft should be able to sample as low as about 2700 m, or about 550 m above the ground when 10 km upwind of Allen Lake during southwest flow. This usually should be low enough to detect the AgI plume according to the 1987 T&D studies and other similar work. Additional crosswind sampling will be made at increasingly higher altitudes, with about 150 m vertical distance between sampling altitudes, flying over the same ground track until the aircraft is above the seeding plume. Pairs of passes will be made at each altitude to allow AgI plume width estimation with the acoustical counter, and to reduce sampling variability. This procedure will document both the vertical and horizontal dimensions of the seeded volume. A second series of similar stepped passes will then be made in the vertical plane directly over Allen Lake, again oriented approximately normal to the mean transport direction of the AgI plume. This will document the vertical and horizontal extent of the seeded volume as it passes over the barrier crest. After completion of the second profile through the AgI plume, the aircraft will repeat the sampling passes made on the first profile, then repeat the second, and continue alternate sampling of the two vertical crosswind planes through the seeded volume until directed to do otherwise by the FC.

The aircraft will also make a limited number of along-the-wind passes during each mission to observe changes in ice particles, wind velocity and SLW upwind and downwind of the crest. The upwind extent of the SLW cloud is of particular importance. Some of these passes may be horizontal and some may be in a shallow dive, parallel to the terrain slope, to sample as low as possible.

**1.6.6 Ground Sampling.** - High-resolution precipitation and other measurements, as discussed in section 1.5, will be made at Allen Lake and at the crosswind nonseeded control site from the time release of AgI commences until after generators are turned off and all of the seeding agent is expected to be carried downwind of the target. At 10-minute intervals precipitation amounts will be weighed, a microphotograph taken, and snow accumulation collected for later silver content analysis. These data will document changes in time and in space. When it is apparent that the effects of the ground-released seeding plume have been adequately documented by both the aircraft and ground instruments, the generator may be turned off for to document changes with time at Allen Lake. Generator shut down would occur approximately midway through the aircraft mission, when fuel is sufficient for another 2 hours of sampling, as about 1 hour will be required for the AgI to pass beyond Allen Lake after generators are off. This approach was used once during the Bridger Range physical experiments (Super and Heimbach, 1988, fig. 2). That case was very convincing concerning changes in ice particle characteristics with distance crosswind of the seeded zone, and with time after AgI generator turnoff. The obvious increase in IPC associated with the AgI plume rapidly diminished with time after generator shutoff, as the concentration of ice nuclei approached background levels.

The high-resolution precipitation gauge network may be used to compare the area affected by seeding with neighboring crosswind areas. This will depend upon whether the magnitude of the seeding effect is sufficient to be detectable by the gauges (further discussed in sec. 1.7), and how well the position of the seeding plume can be documented from the aircraft data during any given experiment. If the AgI plume meanders a lot with time, or the low-level wind has considerable directional shear, it may be uncertain whether particular gauges are influenced by seeding or not. The site 20 km south of Allen Lake, used to manually collect very high-resolution precipitation data, will likely be crosswind of the AgI plume, which later can be verified by analysis of the snow silver contents. It is not known how well the control site will predict nonseeded precipitation characteristics for the target due to natural short-term variations in time and space. Until such data are collected during nonseeded periods, the errors in prediction cannot be estimated with much certainty. However, the control data should be useful in analysis of several combined experiments, and possibly for individual experiments as well.

**1.6.7 Future Modifications to Ground-Based Seeding.** - Analysis of the initial field season's observations should reveal whether ground-based seeding has promise for a significant fraction of Arizona winter storms. If it does, future ground-based seeding experiments will be expanded by incorporation of a network of remote generators capable of targeting Allen Lake over a wider range of wind directions. The network would be radio-controlled as surface travel frequently would be difficult to several of the generator sites. The network would have about 12 generators spaced approximately 3 km apart. Each generator would be equipped with sensors to monitor windspeed, wind direction, and temperature.

## 1.7 Aircraft Seeding Experiments

**1.7.1 General Approaches.** - Physical experiments using airborne seeding will be attempted during periods when ground-based seeding appears unlikely to affect precipitation over the Mogollon Rim. Such periods might have wind directions that would not permit targeting with the ground generators, a lower atmosphere too warm for ground seeding, or cloud bases too high for ground seeding. As with the ground-based experiments, aircraft seeding will not be limited to conditions believed favorable for seeding (abundant SLW cold enough for AgI nucleation, little natural snowfall, and moderate winds normal to the barrier). Attempts also will be made to seed clouds that range from somewhat to very efficient in snowfall production. It is important to determine if seeding can increase the precipitation efficiency of moderately efficient clouds, and whether seeding has any effect on very efficient clouds. Some statistical analyses have suggested that seeding naturally efficient clouds may reduce precipitation while other statistical studies indicate no effect. While there is little physical evidence concerning this question, the observations of Super and Heimbach (1988) showed no microphysical effects in seeded clouds that contained little or no SLW.

The basic approach with airborne seeding will be to use the same aircraft and ground-based measurement systems utilized for detecting the effects of ground seeding, but with the addition of a numerical targeting model to predict where aircraft seeding should be done. A model of limited complexity will be required so computer runs can be accomplished in minutes. The seeding aircraft will be directed to the position the model predicts as most likely to result in snowfall on the target, given that the AgI must encounter SLW near the −6 °C level or colder to create significant concentrations of ice crystals.

The targeting model will probably be a variation of that described by Rauber et al. (1988), adapted to the particular Mogollon Rim terrain. The model will be initialized by special rawinsonde observations with balloons released both well upwind of the target and from the barrier crestline. Additional rawinsondes, and wind information from other sources (e.g., Doppler acoustic sounder), will be used to update model runs during each mission so the location of the seeding line can be adjusted if appropriate. The FC in the project operations center will have access to the model predictions and will inform the seeding aircraft pilot where and when to release AgI.

**1.7.2 Seeding Agents.** - Consideration was given to aircraft seeding with dry ice pellets, which can create ice crystals at temperatures almost as warm as 0 °C. This could be a considerable advantage in the warm Arizona clouds. However, the pellets must be released so as to fall *into* supercooled cloud and this poses two problems. First, there is no practical way to routinely monitor how far the SLW extends upwind of the barrier. Even if an aircraft could be dedicated to sampling the SLW field, supercooled water often would be lower than practical to sample by plane. A line of radiometers could furnish information on the upwind extent of SLW, but at prohibitive cost. Thus, the only means of being reasonably certain that dry ice is dropped into supercooled cloud is by seeding over the higher terrain when the Allen Lake radiometer is detecting SLW. But this is too close to the target to allow for ice particle growth and snowflake fallout prior to the downwind subsidence zone.

The second related problem concerns filling a large volume with seeding material. AgI can be released far upwind in order to widely disperse, through atmospheric turbulence, before the tiny AgI particles finally encounter supercooled cloud droplets. This cannot be done with dry ice, which must fall through supercooled cloud in order to create ice crystals by homogeneous nucleation through momentary cooling of the cloudy air below −40 °C. Similar problems exist with homogeneous nucleation agents that achieve cooling by expansion (e.g., propane or compressed air). Moreover, they must be released directly into the cloud. Because of these problems, and the fact that an AgI seeded volume can be readily detected with an acoustical counter while a volume seeded by homogeneous nucleation cannot be tracked, it was decided to use only AgI in the physical seeding experiments.

One of two types of AgI will be used on any given aircraft seeding mission. The first type to be tested will be fast acting, because residence times in SLW cloud may be limited before the seeded volume passes downwind of the crestline into the lee subsidence zone. Daxiong and Finnegan (1989) described the addition of NaCl to provide a condensation-freezing mechanism which dramatically increased the rate of ice crystal formation. The AgI also needs to be effective at the relatively warm temperatures common in the lower, wetter cloud regions. This argues for a AgI-AgCl nucleus aerosol as described by DeMott et al. (1983) which appears to operate by the contact-freezing mechanism. Deshler et al. (1990) showed significant ice nucleation as warm as −6 °C using $AgI-NH_4I-NH_4ClO_4$ burned in acetone, which produces AgI-AgCl nuclei. Caution needs to be exercised in choosing the specific type of AgI because some of the recent formulations, such as that discussed by Daxiong and Finnegan (1989), are very corrosive to generators making them impractical for field use. A type of AgI, probably one which operates by condensation-freezing, will be chosen shortly before the start of field experiments, to take advantage of any recent developments in ice nucleation research.

The second type of AgI that will be tested is $AgI-NH_4I$ in acetone which produces a relative pure AgI crystal believed to act as a contact nucleus. It is, therefore, slower acting which may be advantageous in some situations. As argued by Fukuta (1986), it is self limiting against overseeding. Because nucleation may occur over a longer time, the area affected by snowfall may be larger. This type of AgI has been successfully used in many seeding programs the past two decades, and was shown to be effective in the physical experiments reported by Super and Boe (1988) and Super and Heimbach (1988). It may not be as effective at warmer temperatures as some more recently developed types of AgI, but some testing indicates the larger particles produced by burning a 4-percent (by weight) AgI solution markedly enhances its warm temperature nucleation as compared with the more common 2-percent solution. Further testing needs to be done in actual clouds to document the effectiveness of all types of AgI seeding agents. In view of the proven operational convenience of $AgI-NH_4I$ and its other favorable characteristics, it should be compared with AgI-AgCl in Arizona winter clouds. Accordingly, it will be tested during some of the airborne seeding experiments. The most effective and practical type of AgI needs to be documented prior to any future statistical experiment.

**1.7.3 Experiments With an AgI Plume.** - Two types of seeding patterns will be flown. In the first, the seeding aircraft will orbit over a point while releasing a single plume of AgI that is transported along the wind. This approach will be discussed next as it closely parallels the ground-based seeding described in section 1.6. Section 1.7.4 discusses the second type of pattern in which the aircraft will release lines of AgI across the wind.

During some experiments the seeding aircraft will circle around a fixed location while continuously releasing AgI. This will result in a plume of AgI drifting downwind from about a 3-km-diameter source. Periodic chaff releases will permit the FC to monitor plume direction and speed, at least until the chaff is lost in precipitation returns. This information, together with reports of plume position from the cloud physics aircraft, will allow the FC to radio position corrections to the seeding aircraft to insure the plume is transported over the target.

For this type of seeding, the cloud physics aircraft will fly mostly crosswind passes through the plume from as low as permissible to above the plume of AgI. However, at the beginning of each experiment the cloud physics aircraft will make a single pair of crosswind passes 300 m above the altitude of the seeding aircraft and about 20 km upwind of Allen Lake. The vertical separation provides for aircraft safety, and it is also likely that the AgI will be transported upward as it approaches the barrier due to forced uplift of the airstream. As with the ground seeding experiments this initial pair of passes will attempt to establish that the AgI is being transported toward the target. If it is not, an appropriate adjustment will be made in the seeding aircraft position.

After proper transport is established, further sampling will be done in two vertical sections, much as in the ground seeding experiments. The first vertical section will be about 10 km upwind of the target to sample ice particles that have likelihood of settling to the surface on or near Allen Lake. The second vertical section will be directly over the target to ensure the seeded volume passed over it, and to indicate where seeding effects might occur further downwind. These stepped passes will be approximately normal to the mean wind in the seeded layer. The main difference from the ground seeding experiments will be that the aircraft-released AgI plume will be higher above the terrain, where the atmosphere is usually colder and turbulent dispersion is less. Occasional along-the-wind passes again will be made by the cloud physics aircraft to investigate the upwind extent of SLW.

After the seeding plume is monitored over the target for approximately an hour, seeding will stop for 45 minutes. The cloud physics aircraft will continue to sample upwind of and over the target, monitoring changes with time as the seeded volume passes downwind of the aircraft so natural cloud is measured, and later as the new seeding plume becomes established. As noted earlier, the combination of showing seeding related changes in both space and time is very powerful physical evidence for seeding effectiveness.

Surface sampling during orbiting aircraft seeding will be similar to that discussed for ground-based seeding and at the same frequency. The Allen Lake observations again will be the primary evidence for seeding effects on the surface. The manual observations of snowfall rate, the microphotographs, and the snow samples for silver analysis will be made at a crosswind control site. The precipitation gauge network also will provide possible evidence of the area affected by seeding and the magnitude of the effect.

**1.7.4 Considerations Involved With Releasing AgI Seedlines. -** The second type of aircraft seeding will be the release of crosswind lines of AgI an appropriate distance upwind of the target as predicted by the targeting model. This type of seeding involves a number of considerations. For example, the seedlines should be sufficiently long to minimize the change of missing the target due to errors in the estimated wind directions between the seeding aircraft and the target, or changes in these winds with time during the experiment.

Radar chaff will be released at each end of each seedline so the changing line position can be monitored by the Mormon Lake radar. This should indicate whether the line is being transported in such a direction that some portion of it should pass over the target, presuming the chaff is not masked by precipitation as will sometimes occur. It is probable that the radar will track the chaff for a limited duration as dispersion and fallout will lessen the chaff's detectability with time. The Doppler radar also will provide wind information that will aid assessment of targeting, whether the radar return is from chaff or precipitation.

The along-the-wind dimension of a seedline increases with time due to turbulent dispersion, and the time that surface snowfall is affected should be closely related to the time required for the seedline to pass overhead. A limited amount of research has been done concerning along-the-wind dispersion of seedlines. For example, a detailed case study by Karacostas (1981), upwind of the Sierra Nevada, indicated a seedline width of 5.3 km after 1 hour with a windspeed of 8.5 m/s. This is in excellent agreement with the more comprehensive data of Hill (1980) who reported on dispersion of aircraft-released AgI in winter storms in Utah. The rate of along-the-wind spreading was shown to be related to windspeed. Mean dispersion rates are given in table 1-1 as a function of windspeed. Also given are resulting plume widths and the time to pass over a point target 1 hour after seeding.

**Table 1-1. - Along-the-wind plume spreading (from Hill, 1980)**

| Horizontal windspeed (m/s) | One-edge dispersion speed (m/s) | Plume width after 1 h (km) | Time to pass over target (min) |
|---|---|---|---|
| 5 | 0.35 | 2.5 | 8.3 |
| 10 | 0.76 | 5.5 | 9.2 |
| 15 | 1.18 | 8.5 | 9.4 |
| 20* | 1.59 | 11.4 | 9.5 |

* Extrapolated beyond existing data.

From Hill's data a single seedline would pass over the point target in only about 9 minutes. But the first three airborne seeding experiments of Super and Boe (1988) on the Grand Mesa of Colorado showed seedlines took from 18 to 30 minutes to pass a point with mean windspeeds of 8 to 10 m/s. The increased spreading over the Grand Mesa is believed to be due to stretching of the seeding plume in the accelerating flow over the mesa top. The observations of Hill and Karacostas probably are more typical of an atmosphere less influenced by mountainous terrain. The situation for the gradually rising Mogollon Rim may be somewhere between the Super and Boe and the Hill results. So a single seedline may affect surface snowfall for only 10 to 20 minutes, or even less if the targeting model specifies release of AgI significantly closer than an hour's travel time from the target. In many cases the resulting precipitation amount should be too small to observe even with high-resolution gauges that resolve near 0.05 mm. A similar gauge was used in early 1987 at Happy Jack which had a median observable precipitation rate of only 0.4 mm/h (these frequent light rates made up only 11 percent of the total seasonal precipitation). Such a rate would yield only 0.07 mm in 10 minutes.

It might be argued that seeding experiments which show precipitation increases less than the natural median rate cited may be scientifically interesting but have little practical value. But such experiments demonstrate all physical processes are operating as hypothesized. The lack of abundant SLW may be all that is limiting the snowfall, as it does with natural snowfall, and similar seeding may be much more effective during the infrequent periods with plentiful SLW. Therefore, seeding experiments that produce even very light snowfall have practical value as proof of concept.

Consideration was given to using multiple seedlines so that the target would be affected for a longer duration during each seeding attempt. For example, if it was desired to influence surface snowfall for at least 30 minutes, table 1-1 suggests three seedlines would be required, if released an hour upwind. But volume filling becomes a concern with multiple seedlines. A sawtooth-shaped pattern will result, caused by the wind transporting the AgI downwind as the aircraft flies back and forth across the wind. However, it is desired that dispersion cause the individual seedlines to merge into a continuous seeded volume prior to approaching the target. Otherwise, unseeded regions within the presumed seeded volume may reduce seeding effectiveness. Again using the data of Hill and a release line 1 hour upwind of the target, two seedlines should be released over the same ground track within 10 minutes for merger to occur before the target is reached. A typical light twin seeding aircraft can be flown at about 93 m/s (180 knots) groundspeed. Given that 1 minute is required for a 180° turn, the remaining 4.5 minutes per seedline allows for a length of 25 km. A 25-km-long seedline represents an arc, relative to the target site, of 38°, 26°, and 20° for windspeeds of 10, 15, and 20 m/s, respectively. It should be relatively easy to target Allen Lake with light to moderate winds but the chance of missing the intended ground target will increase for stronger winds. And the more abundant SLW cases can be expected with the greater uplift associated with stronger winds, probably making them the most suitable candidates for seeding. The only alternatives are to use additional seeding aircraft, an expensive option, or to lengthen the seedlines resulting in greater chances of not filling some of the intended volume with AgI.

**1.7.5 Experiments With AgI Seedlines. -** Experiments during the initial field season will use a single seedline. While effects may sometimes not be detectable by the precipitation gauges, the very high-resolution measurements planned for Allen Lake and one additional site (see sec. 1.5) should reveal any resulting snowfall. Analysis of the first winter's experiments may increase confidence in the targeting model so future seedlines may be shorter. In-cloud measurements of actual seedline widths will be obtained as they approach Allen Lake. With this additional experience and information it may be decided to increase the time of seeding effect by using two to four seedlines per trial in future field seasons.

The initial season's seedlines will be about 40° of arc, relative to Allen Lake. Experience indicates this long a seeding line is very likely to result in the seeded volume passing over the target. The seeding will be accomplished at the upwind distance specified by the targeting model for a release at the −6°C level. The seeding agent will be transported somewhat higher (colder) as it approaches the high terrain and ice particles should form if SLW is present. Additional seedlines will be released such that at least 30 minutes of unseeded cloud passes the target between seeded volumes. These periods of natural cloud and precipitation will provide the primary basis for comparison with seeded cloud over and at the surface target. That is because precipitation gauges crosswind from Allen Lake will often be potentially affected by the same seedlines intended to influence the target due to the length of the seeded zone. Upwind and downwind gauges may offer some basis for comparison if they receive precipitation, presuming the cloud physics aircraft clearly depicts the seedline position as it passes over the gauges.

When the seeding aircraft releases lines of AgI across the wind, the cloud physics aircraft will fly passes along the wind directly over the target, traveling far enough upwind (or downwind) to pass through the seeded zone. These passes will vary in altitude from as low as practical to just above the seeded volume. With approximately a 30-minute transport time between seedlines (equivalent to 18 km for a 10-m/s wind), the cloud physics aircraft often may penetrate two seedlines on a single pass along the wind.

During airborne seeding experiments, the cloud physics aircraft and ground observing systems will attempt to document changes with time for ice crystal characteristics, snowfall rates and other parameters as discussed in sections 1.5 and 1.6. However, manual observations will be made more frequently than during experiments with a plume of AgI because of the limited time of passage of each seedline. Very high-resolution precipitation rate observations and microphotographs will be made every 5 minutes, and snow samples for silver analysis each 10 minutes, both at Allen Lake and at a second protected clearing about 5 km further north. The purpose of the second target site will be to increase the changes of detecting a seeding effect should it not be observed at Allen Lake. For example, due to natural variability, the seedline crossing Allen Lake might not encounter SLW during some experiments, even when SLW exists upwind of the secondary target site.

The cloud physics aircraft data and various wind observations will be used in post hoc analysis to estimate whether seeded or nonseeded cloud volume was over the target at any given time. Super and Boe (1988) demonstrated this general approach. The silver content of the falling snow will also help in assessing whether or not seeding was affecting the target.

**1.7.6 Seeding Aircraft Observations.** - When not involved in releasing AgI, the seeding aircraft will attempt to document how far upwind of the barrier SLW extends at the release altitude and below it. This will be done on a noninterference basis with the cloud physics aircraft, which may be making along-the-wind passes. Therefore, close coordination will be required between the aircraft. The seeding aircraft will always maintain vertical separation from the cloud physics aircraft. Occasionally the seeding aircraft will make a vertical sounding of the atmospheric stability over the windward slope of the barrier, between the two rawinsonde sites. Chaff releases will be made during these soundings in attempts to document the wind velocity at selected altitudes with the scanning radar.

## 1.8 Additional Physical Experiments

**1.8.1 Convective Cloud Seeding Potential.** - Physical experiments that do not involve release of seeding agents will be conducted with isolated and semi-isolated convective clouds that form over the Mogollon Rim several times each winter. An initial examination of this cloud type by Super et al. (1989) suggested they had little precipitation augmentation potential because of a low frequency of occurrence, wide spacing among cloud elements, high efficiency in natural ice particle production in some cases and brief cloud lifetimes. But they also cautioned that these conclusions were tentative, based on a very limited sample, and recommended that further studies be conducted with standardized flight plans to monitor the lifetimes and precipitation mechanisms of these clouds. Their precipitation potential could then be evaluated with more certainty.

Convective cloud studies will focus on cloud lifetimes, in terms of the existence of significant SLW as opposed to visual lifetimes, and on the natural precipitation efficiencies. To the extent that these clouds have brief lifetimes and/or high precipitation efficiencies, their water augmentation potential is nil. Short lifetimes limit the precipitation potential of many summer convective clouds as shown by Cooper and Lawson (1984) and Schemenauer and Isaac (1984). The same phenomena was observed in winter convective clouds over the Sierra Nevada, with entrainment of dry air quickly depleting the liquid water contents (Dragomir, 1989). It is anticipated that most small to moderate-sized convective clouds over the Mogollon Rim also will have short SLW lifetimes, and will produce little precipitation. However, this expectation needs to be tested by actual observations. Moreover, the precipitation efficiency should be documented for those clouds that last long enough to potentially produce precipitation-sized particles. Both these goals can be met by the measurements to be discussed.

**1.8.2 Convective Cloud Sampling.** - Some of the instrumentation systems to be used for physical seeding experiments will also be applicable for convective cloud studies. There should be no conflict in availability because the convective clouds occur at different times than the widespread layer clouds that will be seeded. The cloud physics aircraft will be the primary system needed for convective cloud investigations and the radar will also provide valuable measurements.

It will be useful to follow the sampling and analysis procedures of Schemenauer and Isaac (1984) who provided a data set of 156 natural cumulus clouds from three locations in North America. This will allow easy comparison between Arizona clouds and the clouds they studied. Clouds to be sampled will meet the following criteria: depth greater than 1 km, solid and growing appearance to the cloud top with top temperature between −5 and −20 °C, and isolation from neighboring clouds. In addition, clouds close to the radar will be given preference. The scientist in the cloud physics aircraft will visually select clouds, attempting to first penetrate them early in their life cycle with top temperatures near −6 to −8 °C when practical. The first sampling pass will be made about 300 m below cloud top or at −10 °C, whichever is lower. Subsequent passes will be attempted within a 100 m altitude of the first pass, and passes will continue until the top falls below the sampling altitude, or the average liquid water content falls below 0.1 $g/m^3$. The aircraft will then search for additional clouds to sample in the same manner, and continue measurements until suitable clouds no longer exist or a low fuel level requires termination of the mission.

Occasionally, larger clouds (cumulonimbus) may be found over the experimental area during winter. The above sampling procedures will be adapted to any flanking feeder cells that are found attached to such small- to moderate-sized cumulonimbus. The main portion of cumulonimbus clouds will not be penetrated for reasons of safety.

During aircraft sampling of convective clouds the radar will make frequent sector scans through the volume of atmosphere containing the cloud field under study. This will provide observations of first echo development within the aircraft-sampled clouds, and precipitation below their bases. Post hoc analysis will combine the radar observations with aircraft measurements, particularly of the time histories of cloud liquid water content and ice particle formation. The cloud lifetimes will be compared with calculations of time required for ice crystal growth to precipitation sized particles. The natural ice crystal formation will be related to cloud-top temperature and cloud lifetime, and also to the broadness of the cloud droplet size distribution (Hobbs and Rangno, 1985). In this manner an assessment will be made of seeding potential. It may be that a sizeable fraction of the clouds exist long enough for precipitation formation, but fail to produce rain or snow because of lack of natural ice crystals. If this proves to be the case, further investigation of convective clouds may be warranted, to determine whether seeding could provide useful amounts of additional precipitation.

**1.8.3 Climatological Studies.** - It is recommended that some observations be routinely made 24 h/d that would not be part of the physical experiments. They are climatological in the restricted sense that they would be obtained for the duration of each winter's field season. These measurements would be made with some of the instrumentation systems required for the physical experiments which can operate unattended so observational costs would be minimal. These observations would provide a valuable longer term context in which to place the short-duration physical experiments, and would be very useful for design of future randomized seeding experiments.

The specific measurement systems that should be routinely operated include the precipitation gauge network (which would continue to record data in any event), the microwave radiometer, the Doppler acoustic sounder, the radar in a slow scanning mode, the aspirated 2D-C ice particle imaging probe, and the tower-mounted wind, temperature, and moisture sensors at Allen Lake. These instruments could provide a wealth of information on storm structure and evolution. Some of the analyses of Super et al. (1989) could easily be expanded. For example, the availability of SLW and natural precipitation characteristics could be considered for a much larger storm population. The flux of SLW could be related to storm phase, cloud depth, wind velocity, and precipitation rate to increase insight into potential seedable periods. The factors causing precipitation could be investigated to better understand when and why storms are naturally efficient or inefficient. Such studies would significantly aid design of the next experimental phase; that is, a statistical seeding program aimed at demonstrating long-term increases in snowfall over a large area.

## 1.9 Precipitation Amounts and Area Affected by Seeding

**1.9.1 Introduction.** - The physical seeding experiments will attempt to target a single well-instrumented site at Allen Lake. However, in practice, seeding-caused snowfall will extend some distance in all directions from the intended target site because of (1) limitations in the numerical targeting model, (2) variations in horizontal windspeed and direction in space and time, and (3) variations in ice particle growth rates and fallout speeds depending upon the specific vertical motion field and temperature and liquid water environment encountered. However, the maximum effect on a seasonal basis should be at or very close to the Allen Lake target.

It is beyond the current state of knowledge to specify the exact boundary outside of which seeding has absolutely no effect for any given experiment. However, when the minor amounts of snowfall in the area of *maximum* effect are considered later, it will be seen that the exact specification of the "no effect boundary" is academic. This boundary will be estimated, but with the caveat that specification may be improved as numerical airflow and cloud physics models are adapted and applied to the region of interest. The area of effect for seeding experiments will be considered in light of the experience of similar past experiments, since no model has yet been applied to the region in question. The results from prior experiments should be considered only approximations for the Mogollon Rim because of differences in cloud characteristics and seeding approaches. However, they do provide evidence from physical measurements. The along-the-wind dimension of the target area will be discussed first.

**1.9.2 Target Area Dimension Along the Wind: Aircraft Seeding.** - Only a limited number of successful physical cloud seeding experiments have been reported, and most of these gave no information on the areal extent of the seeding effect, being concerned only with a point target. One exception is Weickmann (1974) who presented two aircraft seeding cases in winter clouds over Lake Erie. Radar observations showed along-the-wind spreading of the seeded areas, some distance above ground, amounted to about 15 to 25 km. The affected surface area was likely somewhat less. Hobbs (1975) describes three case studies with aircraft seeding in the Cascade Mountains of Washington. Data from four instrumented ground sites suggests the distances affected by seeding ranged from about 16 to 30 km along-the-wind. Hobbs et al. (1981) reported one case of aircraft seeding where precipitation fell at the observing radar for about 3 minutes, equivalent to only a 1.3-km distance at aircraft-level windspeeds. Vertical-drop pyrotechnic flares containing AgI or dry ice pellets were used in all but one of these six case studies so seeding was done in the vertical plane below a horizontal line (the flight track). Consequently, the area of effect should be less from each seedline that passes over the Mogollon Rim. Super and Boe (1988) reported on six such releases upwind of the Grand Mesa of Colorado. Of the three cases that clearly precipitated on the surface, only one appeared to produce snowfall over the entire 7-km along-the-wind extent of the mesa top.

The cited investigations suggest that aircraft releases of single lines of AgI upwind of the Mogollon Rim are unlikely to affect more than a 10- to 20-km along-the-wind distance. The affected region should be over the highest portion of the rim since (1) that is where the experiments will be designed to produce snow, and (2) it will often be impossible to target snow at lower elevations due to evaporation/sublimation losses below cloud base, especially in the subsidence zone downwind of the crestline. Further, (3) the SLW zone would need to extend far upwind of the rim for ice particle growth and fallout to occur many kilometers upwind of the crest. That is because ice crystal growth will be limited until the seeding agent encounters the liquid cloud.

Observations during the 1987 winter field program indicated the Verde Valley, located 40 to 50 km upwind of Happy Jack for typical flows from the southwest quadrant, frequently had no more than scattered to broken cloud cover during storms. This clearing was presumably due to subsidence downwind of the Black Hills which form the west boundary of the Verde Valley. While future numerical modeling runs will help clarify the issue, simple calculations suggest that it will often be difficult to target seeding-induced snowfall more than approximately 20 km upwind of the crestline. Observations from 1987 also suggest that subsidence clearing of the clouds is common by 20 km downwind of the crest of the Rim. Certainly precipitation rapidly decreases east of the crest as evidenced by a rapid transition from tall pines to shrubs to grasses, indicating a typical "rainshadow" effect.

Concerns about possible "downwind effects" or "extra-area effects" of cloud seeding frequently are expressed by the general public. These concerns usually are based on misconceptions about the atmospheric processes that produce precipitation. The atmosphere is assumed to function like a river so that if some water (precipitation) is removed, there is less available downstream. In fact, the situation is far more complicated in the atmosphere. Cloud *liquid* water must exist for precipitation to form. But the amount of liquid water in winter clouds is always a small fraction of the amount of water *vapor* in the atmosphere. If the atmosphere is lifted by some mechanism, such as a cold front passage or forced lifting over a mountain (orographic lifting), the air may be cooled sufficiently for a small portion of the total vapor to be converted to liquid. In the case of orographic lifting, the air moves downslope and warms to the lee of the mountain barrier so the liquid water quickly evaporates back into the vapor form. Thus the liquid necessary for precipitation formation is available for a brief time during passage over the barrier. If some of that liquid is removed by cloud seeding, less can be converted back into vapor downwind of the mountain, but the total water vapor contained in the atmosphere is reduced by a very small amount. A much more important factor in determining downwind precipitation amounts is whether or not the atmospheric again will be lifted to produce more liquid. The airflow usually is southwesterly during SLW periods over the planned experimental area (Super et al., 1989), and the next orographic barrier is about 200 km downstream. So any lifting closer to the experimental area must be caused by large-scale motions in the atmosphere, such as the cold fronts and low pressure regions shown on weather maps. Their influence will far outweigh any reduction in total water vapor caused by seeding.

Some statistical analyses have suggested either increases or decreases in precipitation may have resulted downwind of operational and experimental seeding projects. However, no convincing evidence exists that such effects have been detected. Downwind effects, more than about 20 to 30 km beyond the Mogollon Rim crest, are expected to be nondetectable for two reasons. First, the airflow carries storm clouds downslope into a region of higher pressure with associated heating of the air. As just discussed, this creates a natural rainshadow area where precipitation should not be significantly influenced by even routine cloud seeding. Second, the limited amount of seeding during the physical experiments should have little effect even on the target. Mixing of the air will cause dilution of the seeding agent further downwind so any seeding effects would be reduced for this reason as well.

**1.9.3 Target Area Dimension Across the Wind: Aircraft Seeding.** - The across-the-wind dimension of the affected area will be primarily determined by the length of the seeding line for any given experiment. The seeding line will be made long enough to insure that it passes over the target point, realizing that the wind direction usually has spatial variations (wind shear), and can change with time over the duration of an experiment. In addition, some uncertainties exist concerning the actual wind velocity at the start of an experiment, and the accuracy of the targeting model predictions. As a consequence, seeding lines will be released assuming that total targeting errors of approximately plus or minus 20° are possible. For a seedline released an hour's travel time upwind of the target, this translates into 26- to 52-km across-the-wind distances for typical 10- to 20-m/s winds. When model predictions dictate seeding should done closer to the target, the 40° of arc seedlines will be shorter.

For most cases it appears that the area affected by physical experiments using aircraft seeding will be no more than 40 km perpendicular to the wind by 20 km along-the-wind. The along-the-wind precipitation "footprint" will not always be centered on the target, however, due to errors in windspeed estimates and numerical model predictions. The "footprint" may be offset, upwind or downwind, possibly by as much as 10 km. Therefore, the overall target area impacted by *all* the airborne seeding experiments may be approximated by a circle of a 40-km diameter, centered on the Allen Lake target. However, it should be realized that only a fraction of this total area would be impacted during any single experiment. The area that would be affected drains into the Verde and Little Colorado drainages.

**1.9.4 Target Area Dimensions for Ground-Based Seeding.** - The target area will be somewhat smaller for ground seeding experiments. Along-the-wind dimensions should be less than for airborne seeding because only about the lowest kilometer of the atmosphere will be affected, so less wind shear is available to disperse the ice particles. This assumption is supported by the T&D observations reported by Holroyd et al. (1988), Super and Heimbach (1988), and Super et al. (1989), who also indicate that the crosswind spreading from a single generator will usually be in the 5- to 10-km range by the time the target is reached. Plume overlap is highly desirable for the physical seeding experiments so three generators will be located normal to the wind with a 3-km spacing between them, which should result in combined plume width of about 10 to 15 km. Thus, the overall target area for ground seeding will be a subsection of the airborne seeding target.

**1.9.5 Precipitation Amounts and Rates due to Seeding.** - Only limited precipitation amounts and rates are expected from the physical seeding experiments, no matter which seeding method is used. That is partially because of the brief duration of each seeding event. In the first place, it is likely that only one cloud physics aircraft and crew will be available, so most studies will be conducted during daytime or evening hours. That would exclude approximately half of all seedable hours from the possibility of seeding. Experience has shown that no more than two aircraft missions are practical per day, each with the aircraft on station about 3 to 3.5 hours. This further reduces the possibility of seeding to less than 7 h/d (29 percent of all hours). Secondly, both airborne and ground seeding will be limited to fractions of the total observational time because of the need to collect nonseeded data for comparison. Typically, only one seedline will be released per 40 to 60 minutes, unlike the continuous seeding of an operational project, so seeded cloud will pass over the target less than half of the total experimental time. Similarly, both ground generators and aircraft generators during orbiting flight will be operated only about half the time during each experiment. Assuming the combination of ground-based and aircraft seeding would average 40 percent of the on-station time, no more than 12 percent (0.29 x 0.40) of any day's time would be seeded. Operational programs that seed whenever suitable clouds exist rarely claim more than

10- to 20-percent seasonal increases in precipitation. Assuming such claims are reasonable for the sake of comparison, seeding only 12 percent of the time should result in only 1- to 2-percent seasonal increases, unless the experimental seeding is much more effective than operational seeding. Such small increases are much less than the measurement errors of conventional gauges used to measure precipitation. They can only be detected with the sophisticated observing systems and measurement approaches previously discussed.

The final limitation on precipitation amounts and rates is provided by the natural rate of condensation of liquid water. The rate of cloud liquid water flux over the barrier is the absolute upper limit for precipitation production for either natural or seeded snowfall. We will first examine actual measurements of seeding-induced snowfalls from various project areas, and then consider probable rates over the Mogollon Rim estimated from observations of cloud liquid water flux.

Reynolds (1988) reviewed the published magnitudes of directly measured precipitation increases due to seeding from all available winter orographic physical experiments. He noted that increases from the five airborne seeding studies ranged from 0.1 to 0.9 mm/h (all precipitation values are melted water equivalent). The durations of seeding effects at the surface ranged from only 5 to 10 minutes per seedline in some studies to no longer than 40 minutes. Thus, the hourly precipitation accumulation for a single seedline would be well under 1 mm (1-cm depth for a typical snow density of 0.1).

The only available evidence from ground seeding experiments was from two studies that did not have surface precipitation measurements, but estimated precipitation rates from aircraft observations. These are probably underestimates because of known instrumentation limitations and the likelihood of further ice particle growth below aircraft levels. The published rates of 0.05 to 0.2 mm/h are estimated to be low by a factor of two or three so surface rates for the ground seeding experiments were likely similar to the airborne seeding cases. Thus, for either type of seeding, it is estimated that average seeding-induced precipitation rates will rarely exceed 0.1 to 1.0 mm/h, with hourly accumulations usually less than 0.5 mm.

Cloud liquid water flux observations over Happy Jack were compared with precipitation rates by Super et al. (1989). Portions of tables 5-3 and 5-4 from that report are reproduced here for consideration. It is assumed that all the flux is converted to precipitation that falls uniformly over a 10 km along-the-wind distance to allow consideration of equivalent precipitation rates, easier to comprehend than flux values. If the precipitation fell uniformly over twice (half) the 10-km distance, the rate values of table 1-1 would be halved (doubled).

**Table 1-2. - Distributions of hourly cloud liquid water fluxes and corresponding precipitation rates assuming all the flux is converted to uniformly deposited precipitation over a 10-km distance**

| Hourly flux (grams x $10^6$ per meter crosswind) Range | Midpoint | No. of hours in range | Precip. rate for midpoint (mm/h) | Total precip. (mm) |
|---|---|---|---|---|
| 0.1 to 1.0 | 0.5 | 114 | 0.05 | 5.7 |
| 1.1 to 3.0 | 2.0 | 112 | 0.2 | 22.4 |
| 3.1 to 7.0 | 5.0 | 83 | 0.5 | 41.5 |
| 7.1 to 15.0 | 11.0 | 43 | 0.5 | 47.3 |
| 15.1 to 31.0 | 23.0 | 12 | 2.3 | 27.6 |
| 31.1 to 63.0 | 47.0 | 5 | 4.7 | 23.5 |
| Totals | | 369 | | 168.0 |

Table 1-2 shows that the distribution of cloud liquid water flux is highly skewed with a much higher frequency of smaller values. Consequently, the *maximum* precipitation rates that could be derived from the liquid water passing overhead are approximately 0.2 mm/h or less for 226 hours, or the 61 percent of all hours with smallest liquid flux amounts. Only rarely could precipitation rates approach 5 mm/h, and then only if seeding was 100 percent effective in converting SLW to snowfall, an unlikely event.

The median and mean hourly precipitation rates for the same 2-month period at Happy Jack were 0.36 and 0.86 mm/h, respectively, and the maximum rate observed was 6.05 mm/h. These values are in general agreement with table 1-2, suggesting that conversion of the available flux to roughly a 10-km along-the-wind distance is reasonable.

We will now estimate how much additional snowfall might have been produced by physical seeding experiments during the 2-month observational period of 1987, considered to be a little wetter than normal by Super et al. (1989). Let it be optimistically assumed that (1) seeding experiments could be conducted on 29 percent of the 369 hours with observed cloud liquid water, again presuming availability of one field crew so flight could take place up to 7 h/d; (2) 40 percent of the experimental hours would actually be seeded with the remaining time used in mission coordination and sampling of nonseeded cloud; (3) seeding attempts would encounter the same SLW distribution shown in table 1-2; and (4) seeding efficiency would be less than 100 percent. It is difficult to estimate what seeding efficiency might be. Most past physical experiments have been unable to demonstrate marked SLW reductions, suggesting the conversion of SLW to snowfall has been well under 100 percent. The seeding efficiency will be optimistically assumed to be 50 percent for the purpose of estimating seeding-induced snowfall amounts. Then the total additional snowfall for the 2 months would be the 168 mm of table 1-2 adjusted by the factors noted, or 168 mm x 0.29 x 0.40 x 0.5 = 9.7 mm. The Happy Jack snowfall during the same period was 220 mm, so the estimated 9.7-mm enhancement would represent a 4-percent increase over what nature produced.

It was previously estimated that seeding only 12 percent of the total hours should result in no more than 1- to 2-percent seasonal increases, presuming that 10- to 20-percent increases claimed for operational projects are correct. [In fact, it has proven very difficult to provide scientifically convincing evidence of significant snowfall increases even from experimental projects (American Meteorological Society, 1985)]. It seems unlikely that the physical experiments planned for the Mogollon Rim would result in as much as a 4-percent increase in seasonal precipitation. It should also be recalled that the above estimates are most applicable to the near vicinity of the Allen Lake target, and the frequency and magnitudes of seeding-induced snowfalls will decrease in all directions from there. Hence, as the boundaries of the overall target area are approached, precipitation increases due to the physical seeding investigations are unlikely to exceed 1 percent of the natural snowfall during the experimental field season.

To place the likely high estimate of a 4-percent maximum increase in better perspective, we will consider the monthly precipitation totals at the Mormon Mountain Snotel site, 15 km north-northwest of Allen Lake and at almost the same elevation. For the period 1961 through 1985, average monthly precipitation amounts for December, January, February, and March were 112, 104, 104, and 132 mm, respectively; the average for all months was 113 mm. Therefore, a 4-percent change would be equivalent to about a 4.5-mm water equivalent in the average month, or about a 5-cm additional snow depth. However, large natural variations exist in the monthly totals, ranging from months with no measurable precipitation to months with several times the average. It is evident that seeding-induced precipitation enhancements would not be noticeable within the much larger natural variations. It is again worth noting that a 4-percent increase in seasonal snowfall is considered the maximum possible from the seeding experiments, not the amount most likely to occur, and the highest increase achieved would be confined to a limited area.

## 1.10 Experimental Coordination and Organization

**1.10.1 General Considerations.** - The following discussion is based on the assumption that resources will permit only a single ground crew and single crews for the two project aircraft. Thus, field operations would be limited to one shift per day, likely during the daytime and evening hours. However, it is strongly recommended that consideration be given to maintaining two crews for all field equipment making possible 24-hour operations. Such coverage would essentially double the number of experiments per field season while the cost increment would be much less than a factor of two. Equipment purchase or lease costs and their setup and maintenance costs are almost the same whether the systems are used on a half-day or full-day basis. Thus, while cost per field season would be higher, cost per experimental unit would be much less if two complete crews were utilized. There would also be a followup reduction in analysis costs as it is more efficient to process twice as much data once software is completed, personnel are familiar with their tasks, etc. The physical experiment phase could be completed sooner, and at lower total cost if two crews were utilized.

**1.10.2 Forecasts and Scheduling.** - Most winter orographic seeding experiments have devoted considerable effort to weather forecasting for project operations scheduling. In the experience of the author, based on several projects across the intermountain West, the state-of-the-art of winter weather forecasting in this region is adequate to predict situations when the next 12 to 24 hours will be storm free (e.g., when high pressure dominates the region). That allows FCs to make the important operational decision to stand down for up to a day with little chance of missing weather suitable for experimentation. Beyond that, FCs should be very cautious. If there appears to be even a small chance of suitable weather developing, field crews should either be put on standby or required to check in within a few hours for an update. No matter who does the forecasting, the weather predictions will be inadequate to *consistently* forecast development of suitable storms or the correct timing of their passage. Relying on forecasts will result in many missed opportunities and, hence, a very inefficient field experiment. It is expensive to maintain equipment and employ full-time field crews, and these costs are essentially fixed no matter how many storms are sampled per season (some relatively minor exceptions exist such as hourly aircraft costs). It is therefore prudent to sample as many storms as possible. This is best done by standing crews down only when it is clear that suitable weather will not exist, and otherwise having crews available in case a storm passes over the experimental area. Thus, except for fixed days off and occasional down days for equipment maintenance or rest when no weather is expected, the field program should operate on a "nowcasting" basis. That means that crews are available and the weather is continually monitored by radar, radiometer, other ground-based sensors and hourly weather observations from around the region. At the first hint of suitable weather development, crews are alerted to go on standby at their respective stations. Intense data collection then begins when the FC believes it appropriate from watching the weather develop. This recommended mode of operation is quite feasible provided the field crews are hired with the understanding that they will spend considerable time in standby status, often waiting for storms that do not materialize, and the FC is willing to keep crews on standby even when the chance of storm development appears minor.

The FC would be based at Flagstaff. He/she will decide the timing and type of physical experiments to be conducted, and will direct overall facility utilization. The FC will have access to complete weather and forecast information from the Flagstaff Airport National Weather Service Office, and also at the project operations center by satellite downlink. A regularly scheduled morning meeting will be held in Flagstaff, led by the FC, with a conference call to the aircrews. Equipment availability and expected weather will be reviewed, and the FC will inform crews about their status. Possibilities range from immediate preparation to launch a mission, to immediate standby while the weather continues to be monitored, to standby at a later time, to stand down for the day allowing routine maintenance, data reduction, etc. Each Sunday will be a day off as experience has shown a fixed day off is best for an extended field season. Attempting to forecast nonweather days to be taken off results in little net gain in successful experiments but considerable crew inconvenience. In addition to Sundays, a few other days off may be granted at the FC's discretion if the weather is obviously unsuitable for operations and all equipment is in a ready status.

In general, whenever the FC suspects that weather suitable for experimentation may develop, he/she will place personnel on standby and drive to the project operations center near Mormon Lake. There the FC will monitor the weather over the project area with particular emphasis on radar and satellite observations of approaching clouds, and on trends of water vapor and SLW above the barrier. Local winds, temperatures, and precipitation rates also will be available at the radar. Telephone and radio will enable the FC to communicate with air and ground crews in order to launch missions, and then to coordinate experiments to maximize their effectiveness.

**1.10.3 Project Crews and Aircraft.** - Most ground personnel will base out of Flagstaff, and drive to the field as needed. Driving time from Flagstaff to the target area is approximately 30 to 45 minutes. Personnel operating the upwind rawinsonde and ground seeding generators may base out of Camp Verde. If resources will not permit backup crews for aircraft or ground facilities, most experiments will be conducted during daylight hours. This enhances the safety of operations; for example, emergency landing sites are much more obvious during daylight should the need ever arise.

Both the seeding and cloud physics aircraft will be based at the Scottsdale airport just east of Phoenix. The only airport closer to the project area with an instrument landing system precision approach, considered essential to all-weather operations, is at Prescott. It was used as the aircraft base in the early 1987 field program. However, hangar space was very limited and one major snowstorm closed the airport for a few days due to lack of plows. All-weather operation would be assured out of the Phoenix area, and hangar space appears to be available at Scottsdale. Moreover, Phoenix has the further advantage of more abundant supplies and services. Flight time to the target will be about 10 minutes more from the Phoenix area than from Prescott.

**1.10.4 Project Organization.** - While several combinations of program organization are possible, the following is recommended. All personnel and functions involved with the maintenance and operation of ground-based field facilities should be the responsibility of a single contractor. The FC would be furnished under this contract and would manage daily activities. The seeding aircraft should be provided by this contractor who also would have responsibility for ground-based seeding. That responsibility includes meeting legal requirements, such as reporting to the National Oceanic and Atmospheric Administration as required by Public Law 92-205, and providing for weather modification insurance. The cloud physics aircraft, its crew and support facilities should be provided by a second contractor, as this is a specialized type of activity. Analysis of data could be handled by a separate contract running concurrent with the field contracts, or could be done by scientists participating in the field efforts if field programs are conducted on alternate winters. The State of Arizona would provide overall program management, and might wish to employ the services of an independent advisory panel for general scientific guidance. The program should employ a chief scientist for technical oversight. This person would not be involved in daily field operations, but would be familiar with them and with analysis progress. He/she would update the experimental design as new information became available, would suggest analysis approaches, and might be the leader of the analysis team.

While it important that all key personnel be experienced, it is of particular importance that both the chief scientist and the FC have a solid scientific grasp of the physical experiments, extensive experience in managing winter orographic cloud seeding research programs, and demonstrated ability to work congenially with a wide variety of people.

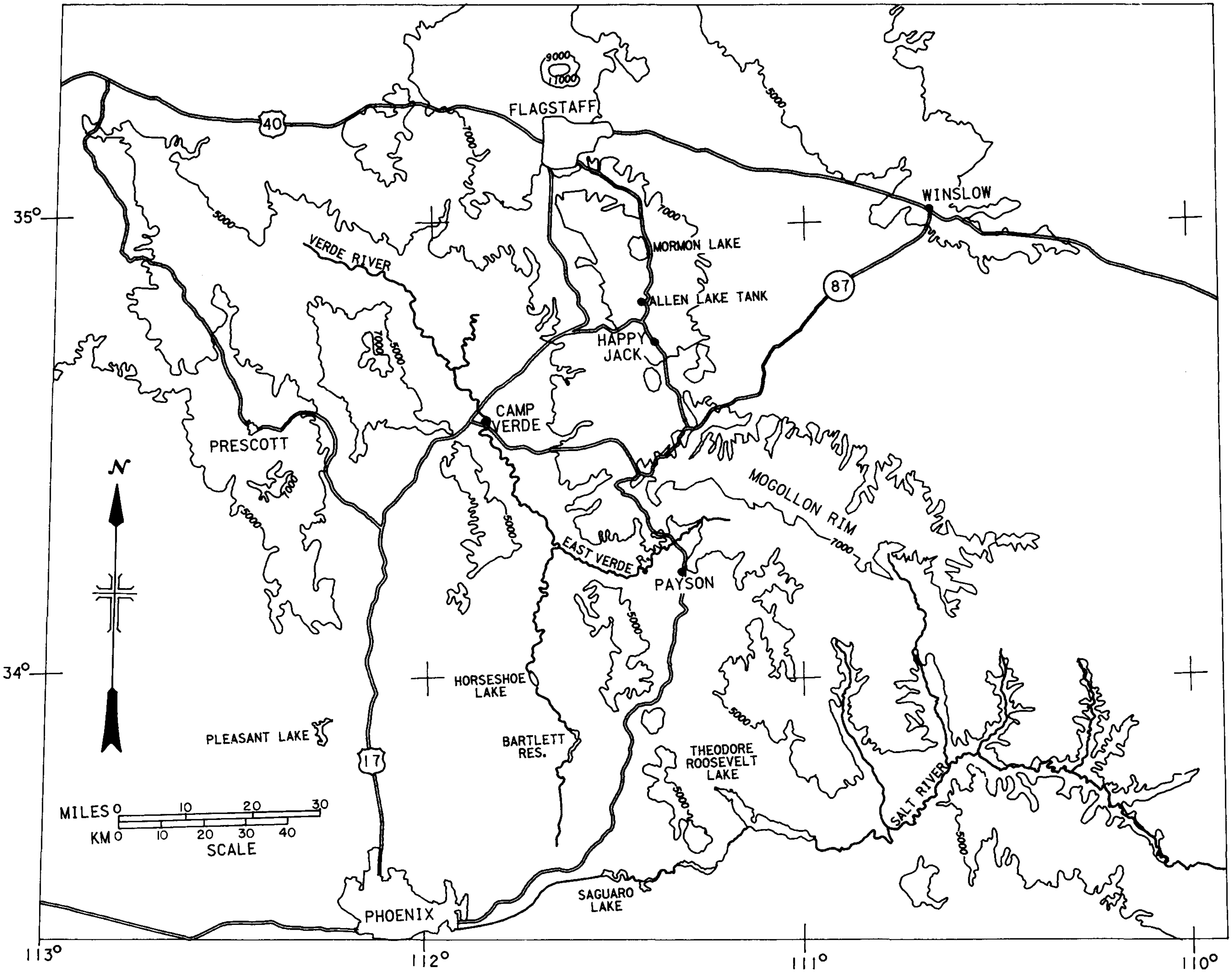

Figure 1.1. - Portion of Mogollon Rim southeast of Flagstaff, Arizona, and surrounding region.

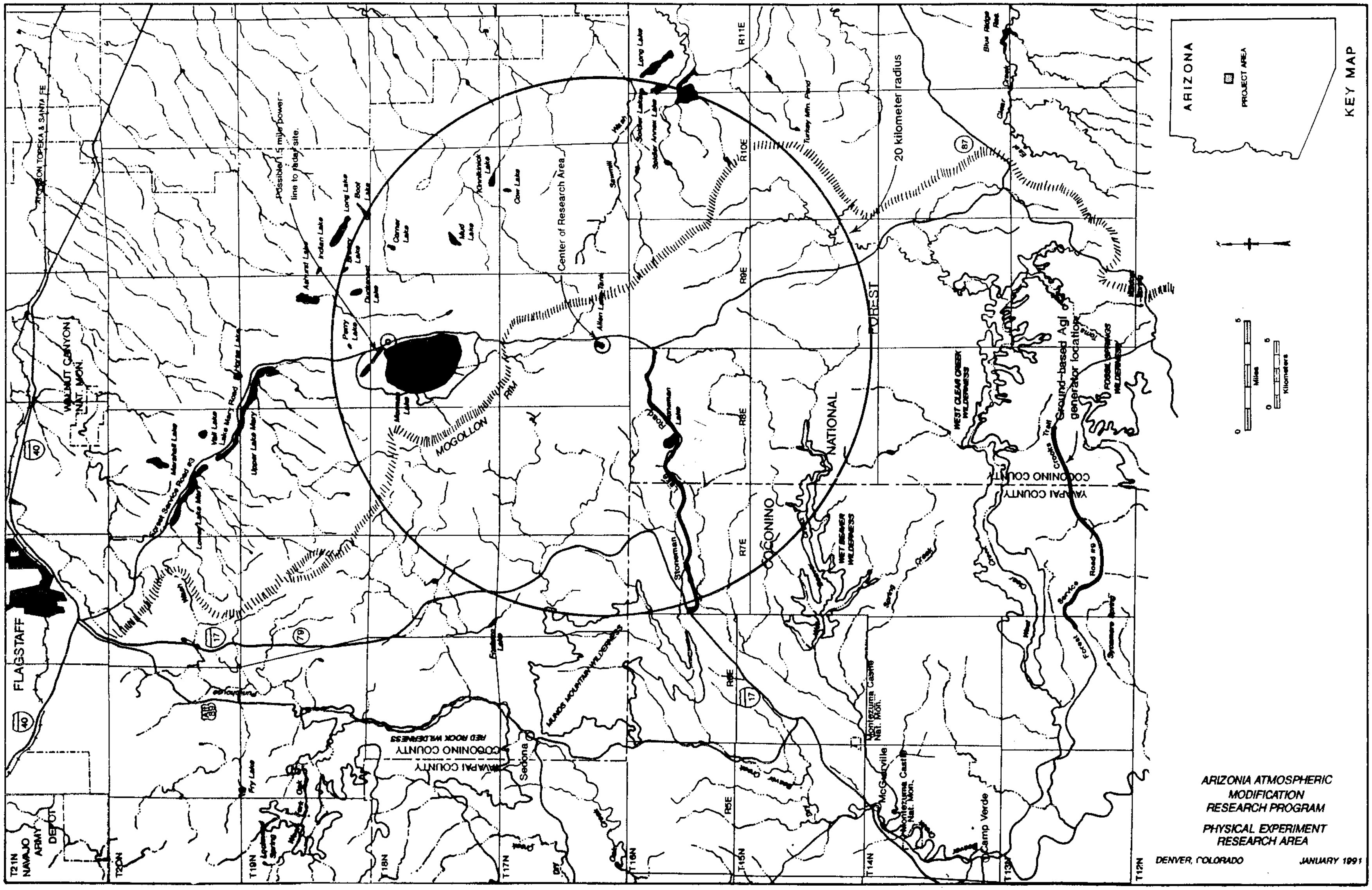

Figure 1.2. - Proposed experimental area centered on Allen Lake Tank and surrounding region.

# 2. DATA ANALYSIS PLAN

## 2.1 Introduction

Field studies and analyses of winter clouds over the Mogollon Rim during mid-January to mid-March of 1987 and 1988 were performed to investigate opportunity and feasibility for precipitation enhancement by cloud seeding. Results of those analyses are given in a report by Super et al. (1989), hereafter referred to as SHM in this data analysis plan. Their efforts focused on the study of (1) availability and distribution in space and time of SLW which are crucial for cloud treatment, (2) occurrence and character of natural ice crystals, (3) T&D of a tracer to simulate seeding, and (4) evolvement and character of weather and cloud conditions that produce precipitation and potentially seedable circumstances.

In their report, SHM concluded that essential SLW existed in at least portions of most of the storms studied. Analysis indicated relatively large amounts of SLW flux at ridge top that were not consumed due to inefficient precipitation processes. Studies indicated rapid cloud transition between apparently seedable and nonseedable status.

Transport and diffusion studies, with a tracer to simulate seeding from the ground (hereafter referred to as ground seeding), indicated that ground-released AgI would generally disperse in the lower 0.5 to 1.0 km above the Mogollon Rim when stratiform clouds prevailed. This layer is frequently too warm in Arizona for the generation of significant numbers of ice crystals by conventional ground-released AgI. Consequently, SHM recommended experimentation with newly developed chemicals that laboratory studies indicate are more efficient at warm temperatures, near −6 °C, that frequently occur in the moist lower layer. T&D studies were recommended in cases of embedded convection which were not researched in the tracer experiments but are common in Arizona winter clouds. The use of upwind high-elevation sites for ground seeding also needs to be investigated. Despite improved ground seeding, SHM indicate that many Arizona storms will require aircraft release of seeding materials (hereafter referred to as aircraft seeding) to achieve proper targeting and so experiments need to be conducted to develop such treatment strategies.

It was recommended by SHM that a several-year physical experiment and analysis program be conducted over the Mogollon Rim to establish the feasibility of obtaining additional precipitation by cloud seeding and to determine and develop proper treatment strategies that could be implemented in a future randomized seeding program. Experimentation and data analyses suggested by SHM would develop preliminary estimates of benefits and costs of cloud seeding. If warranted, a subsequent randomized cloud seeding program could be conducted to demonstrate the technology on sufficient cases to more precisely establish treatment effects over a larger area and to determine confidence levels.

This report proposes in part 1 that the next Arizona field experiments concentrate on the study of physical processes that result from cloud treatment. Therefore, data analyses should be tailored to well describe the evolving processes. Since similar analyses have been performed in experiments conducted in California, Colorado, and Montana in recent years, considerable computer software exists for performing the required analyses. When possible, this software should be used in future Arizona experiments. Required data analysis software should be developed or existing software modified to analyze results from physical studies conducted.

Analyses performed in future Arizona experiments should be oriented to provide answers to remaining key questions including:

1. What is the SLW distribution in time and space upwind of the Mogollon Rim and the conditions that lead to its development? How do these features impact cloud seeding opportunity?

2. What are the impacts of cloud treatment on IP habits and respective concentrations, sizes, and precipitation rates?

3. What are prominent IP trajectories under commonly occurring conditions, including those within the cloud layer a few hundred meters above the rim?

4. What are the character and role of embedded convection and implications for treatment?

5. How often will ground-released AgI result in significant concentrations of ice crystals well upwind of the barrier, so that resulting precipitation falls in desired areas?

6. What are the circumstances when seeding is not beneficial and the degree of potential losses, if any?

In the following discussions on the analysis of experimental data, emphasis is given to manipulating the important parameters to provide answers to the prominent questions and issues regarding cloud seeding feasibility and the development of treatment strategies. Details on the level of how to analyze weather maps or rawinsonde data are not covered. Rather, there is a discussion on when such analysis may be important and should be performed. Descriptions of presentations of key results are included, such as time series of SLW. Frequent reference is made to analyses procedures used by SHM since their studies were conducted recently. Analysis techniques and computer software developed by Holroyd (1987) and Holroyd et al. (1988) or comparable developments are necessary for analysis of future Arizona experiments. Generally, the analysis techniques have been developed and software exists for their implementation. When a choice of techniques is available, those more automated have been suggested.

A few suggestions are in order regarding those performing the data analyses. It is recommended that a team be assembled and a principal investigator selected to direct analysis efforts. The efforts would include data quality testing and preliminary processing for archival; analysis of seasonal field data sets between seasons; and, upon completion of all data collection, comprehensive analyses and interpretation of results. The principal investigator should have previous experience with data analysis teams in weather modification experiment programs. The analysis team should include other individuals with experience in data analysis for weather modification experiments. Ample time and computation resources should be made available to conduct the analysis and report the results.

Physical experiments will be evaluated both individually and collectively by pooling the results of experiments conducted under similar conditions. The general approach to analysis of individual experiments will be to compare aircraft observations within seeded cloud volumes and surface precipitation characteristics under seeded volumes, with similar measurements from nonseeded volumes. The latter may be nearly simultaneous samples obtained by aircraft or surface sensors in or under cloud a short distance crosswind of the seeded zone. This would be the usual approach when plumes are released from fixed sites on the ground or from an aircraft orbiting over a fixed point for periods of 1 to 3 hours. It is assumed, in comparing the seeded and nonseeded regions, that natural variability is relatively limited over the space containing the regions. This approach was successfully used by Super and Heimbach (1988).

When seedlines extend across the wind, nonseeded (control) zones will be determined so that natural cloud before and after (downwind and upwind) a seedline will be compared with the seeded volume. The assumption here is that natural variability is relatively limited for the hour or so required to sample at the target before, during, and after seedline passage. Aircraft sampling along-the-wind through the seedline will be much more rapid than in the case of continuous seeding. Super and Boe (1988) demonstrated this method of comparison.

In either type of seeding, plume or seedline, there is the danger that natural variability will either mask the seeding effect, or result in a misinterpretation of an apparent seeding effect when none actually exists. Averaging over multiple aircraft passes through the seeded and neighboring nonseeded zones during each experiment is a partial safeguard against this danger. Other safeguards are discussed in part 1, such as observing natural changes in approaching cloud structure with radar. An apparent seeding effect must make physical sense in terms of arrival time with the prevailing winds, crystal habits appropriate for seeded cloud region, etc. Further, increases in silver content must accompany any snowfall period alleged to be effected by seeding. Even with these safeguards, measurement errors and lack of complete knowledge of all physical processes involved may in some cases yield erroneous indications of seeding effects. It is believed that the experimental design discussed in part 1 will provide strong physical evidence of actual seeding effects in many experiments conducted.

Sample sizes are expected to be relatively small, given typical storm frequencies in Arizona and the formidable logistics in sampling potential cases. In a 3- or 4-month program (4 months is strongly recommended), experimental units of 3- to 4-hour duration (actual cloud seeding lasting a fraction of each experiment) will be sampled. In some of the analyses, stratification by seeding mode will be necessary as some cases will be treated by ground seeding and others by aircraft seeding and, furthermore, two different seeding agents will be employed in the latter. This means that even though analyses procedures from case to case will be quite similar (e.g., analysis of the 2D-C probe data will be about the same regardless of the seeding mode), the opportunity for analysis on pooled samples is reduced due to the required stratifications.

Analyses of strata that may contain as few as 5 to 10 cases each will be limited to qualitative comparisons of the time series of the responses. When possible, data pooling should be performed to enhance the sample sizes, so that exploratory statistical techniques (exploratory because treated cases are not selected at random) can be used for testing for differences in control and seeded samples. The confidence in results of the experimentation will depend substantially on the number of well-sampled cases.

Our detailed discussion begins with coverage of some general topics including, in section 2.2, establishing a climatology of the experimental area, weather forecasting, and numerical modeling. This is followed by discussion of cloud and atmospheric characteristics in section 2.3, ground seeding analysis in section 2.4, and aircraft seeding analysis in section 2.5. Section 2.3 covers analyses of data from the principal sensors including the radiometer, 2D-C probe, and precipitation gauges. Section 2.6 briefly discusses several additional studies of interest that should be performed. Some comments on refinement of treatment strategies are given in section 2.7. Contributions made by experiments, to develop a design of a randomized seeding program are briefly discussed in section 2.8.

## 2.2 General Characteristics of Storms Observed

**2.2.1 Storm Description and Classification.** - To determine the feasibility of cloud seeding, some climate and storm information is necessary estimate frequencies of occurrence of treatable conditions. Results of attempts to forecast the occurrence of suitable experimental clouds in previous winter cloud seeding experiments have been discouraging. In recent experiments this has led to only modest efforts and, consequently, lessened requirements for analyses of detailed daily weather information. The main procedure recommended for use in Arizona is nowcasting. Nowcasting includes study and interpretation of 30-min satellite photos or satellite photo loops (when available), radar data, hourly NWS (National Weather Service) reports, visual observations by trained observers, and measurements from other project instrumentation including the radiometer and the acoustic sounder. While long-range forecasts appear not feasible, general 6- to 24-hour weather forecasts would be useful to the conduct of experiments and should be developed.

On each day of declared operational periods, regularly scheduled NWS synoptic weather analyses and forecasts, radar summaries, and satellite photos should be available to field personnel. Current measurements from project field instruments including rawinsonde, radar, radiometer, acoustic sounder and surface observations should also be available to supplement the synoptic-scale information and improve resolution in time and space. Runs of an orographic precipitation model and a simplified targeting model using as input the most recent atmospheric sounding should be available. Using all this information, field forecasters should develop forecasts to guide operational plans out to 24 hours. Forecasts should be updated every 12 hours. Information used for developing forecasts should be archived for use in other analyses.

Daily narratives should discuss expected weather and cloud activity over the operational area. At the end of the day or experiment, narratives of actual weather and principal cloud activity should be written and archived. Though nowcasting will be heavily relied upon to declare and guide the conduct of the physical experiments, achieving a useful degree of forecasting capability is desirable for the performance of a future randomized seeding program and subsequent operational seeding. It is recommended that some effort be made to improve forecasting by studying and comparing forecasts and with observed weather and clouds.

Weather data, particularly satellite, radar, and wind data, should be investigated for the occurrence of mesoscale features, such as cloud bands, that may affect cloud seeding opportunity, seeding strategies, and the evaluation of treatment effects. The development of significant blocking layers or a barrier-parallel, low-level jet may alter seeding strategies. Analysts must include in their analyses the search for such mesoscale features.

For operational use, a decision ladder should be developed that uses basic weather parameters, current cloud information, and model run results, and leads to a forecast of cloud occurrence and character, and then refined for future employment in a randomized seeding program. Initially, a decision ladder based on knowledge gained from the 1987 and 1988 experiments should be developed. Contents should be updated and revised as suggested by accumulating information.

The classification system for Arizona storms that was developed by SHM should be applied in the physical experiments. Their classes were synoptic stratiform (SS), synoptic convective (SC), mesoscale stratiform (MS), mesoscale convective (MC), and nonepisode (NE). Definitions for these are given in SHM. Classification once each hour of all storms studied will help to define Arizona storm characteristics and evolution and provide background information to determine their frequency of occurrence.

Cross-tabulation of storm classifications by date and each hour of the 24-hour day should be performed for all storms studied in future Arizona experiments. Frequency and percentage frequency plots with storm type as the abscissa should be developed. By including null events in the cross-tabulation, frequency tables and plots can be developed to show the relative occurrence of storms versus no storms or a particular storm type versus no storms by hour of the day.

In further general characterization of winter storms on the Mogollon Rim, daily, monthly, and seasonal precipitation and ridge top SLW measurements and computed SLW flux amounts should be presented in time series plots (SLW is discussed in much greater detail in sec. 2.3.4). For comparisons with previous Arizona results, future SLW flux estimation should employ the technique presented by SHM.

**2.2.2 Precipitation Modeling.** - During portions of most winter storms, moist air is forced to rise over the Mogollon Rim and some of the moisture condenses, thus generating SLW. Precipitation processes use some of the SLW to produce ice and liquid particles that reach the ground. This natural process, known as the orographic precipitation process, is generally well known and consequently has been modeled employing simple mathematical representations of the most essential physical processes. A local-scale precipitation model was developed and adapted for application to the mountains of Colorado and California by Rhea (1977). Adaptations of this model have been used to develop daily quantitative precipitation forecasts (e.g., Rhea, 1977; Armstrong and Williams, 1981; El Majdoub, 1989) and in the evaluation of weather modification programs (Medina et al., 1979; Matthews et al., 1989).

The precipitation model is two-dimensional, steady-state, and multilayer. It accounts for moisture flow from any direction and "shadowing" by upstream mountain barriers. To achieve these capabilities, the model uses a separate terrain elevation grid for each 10° in azimuth with a point spacing of 10 km. Precipitation is developed at each grid point, or by interpolation, for any other desired location in the model domain. Volume precipitation integrated over desired watersheds and time periods is also computed.

The precipitation model can be run on a microcomputer. As inputs, it requires estimates of the vertical profiles of wind, temperature, and humidity upwind of the area of interest. Since the model is steady-state, frequent updating of the input information improves model estimates.

During 1990 the model will be adapted to Arizona under a 1990 Intergovernmental Agreement and will be available for use in future experiments. It is recommended that runs of this model be made with all project soundings taken during future experiments. The simplicity of the model enables many runs with relatively few resources once the model is adapted and data sets are established.

Model-estimated precipitation volume precipitation integrated over selected watersheds and time periods will be helpful in the characterization of Arizona winter storms, determination of the feasibility of cloud seeding and the development of evaluation procedures for a future randomized seeding program. Estimates of point precipitation and watershed volume precipitation should be compared with available measurements of precipitation and streamflow by scatter plots and correlation and regression analyses. In the case of streamflow, comparisons may only be meaningful with seasonal totals, since snow storage will distort results even with monthly amounts. Model estimates should be pooled after completing all experiments and compared with actual measurements. Model-generated areal mean precipitation should be tested as a possible covariate along with other weather parameters (which ones depend on parameter availability and variability and relationship to areal precipitation). Establishing model-generated precipitation as a useful covariate could enhance the evaluation process in a future randomized experiment.

The adapted precipitation model should also be useful in the development of 6- to 24-hour forecasts. Estimates should be obtained of quantitative precipitation for 3- or 6-hour or at least 12- and 24-h periods, depending on sounding availability. Model estimates should be incorporated with other information in developing forecasts.

**2.2.3 Airflow Modeling.** - Proper targeting of treatment agents is vital to the success of cloud seeding. A targeting model developed for the Sierra Nevada of California by Elliott (1981) and later considerably refined by Elliott and Rhea (1984), Rhea and Elliott (1986), and Rauber et al. (1988) will be adapted during 1990 for use on the Mogollon Rim under a 1990 Intergovernmental Agreement. The model contains a diagnostic technique for targeting both airborne and ground seeding that can be applied on a real-time basis. Guidance is provided on the proper location and orientation of airborne seeding lines or location of ground sources. Estimates of areal coverage of the seeding effect are also produced.

The model is interactive so that the latest information on wind fields and SLW can be incorporated to update results. Because running time is only a few minutes, it can easily be updated as conditions change during an experiment or different scenarios are explored. Minimum required input is sounding information and an estimate of SLW concentration as a function of location. Liquid water estimates can be obtained by the radiometer, aircraft, or both. Results are improved if soundings are available at frequent time intervals such as every 3 hours, and from two locations on the windward slope, one part-way up, and the other near the summit.

The model diagnoses the wind field in the vicinity of the barrier crest to about 100 km upwind. It predicts IP growth rates and trajectories. It determines IP habits on the basis of temperature and particle axial ratios. The model employs a parameterization for riming of IPs dependent on SLW and temperature. Aggregation and ice multiplication are not considered in the trajectory calculations. Aggregation was rarely observed in seeded clouds in the Sierra Nevada during SCPP. Accretion was suggested in SCPP observations to be the primary IP growth mechanism in seeded plumes.

Model simulations can be obtained for seeding by airborne acetone generators which produce a narrow continuous plume, ejectable AgI bearing flares which produce a vertical curtain, or ground generators which also produce a narrow continuous plume. The method that determines the dispersion of the seeding effect takes into account differences in activation time by different treatment agents.

It is recommended that in future Arizona experiments a targeting model which has been adapted to the Mogollon Rim (adapted with the use of 1987 and 1988 experimental results) be utilized for estimates of (1) wind fields, (2) seeding agent application points or lines, and (3) areas of seeding effects. Model results should be compared with aircraft and ground measurements for tracking plumes and seeding effects and adjustments made to model parameters if performance is improved thereby. Comparisons include those of field estimated and modeled IP trajectories. Capability of the model must be assessed for targeting of the seeding agent in various important weather and cloud types and its use incorporated into the development of seeding strategies.

Following completion of all seeding experiments, it is recommended that a climatology of winds be developed from targeting model runs for those storm conditions for which the model produces useful estimates. Tables of the vertical profiles of wind u and v components from the crest to near 100 km upwind should be developed for stormy conditions. Plots of the vertical profiles should be developed for the most frequent storm conditions favorable to cloud seeding. The plots should be useful to the development of conceptual models of seedable storms and respective seeding strategies.

## 2.3 Cloud and Atmospheric Characteristics

**2.3.1 General Comments.** - It is essential that for each experiment conducted, certain cloud microphysical and atmospheric characteristics be determined in order to describe important precipitation processes, atmospheric status during significant cloud activity, and impacts of seeding. Analysis methods recommended are quite similar and in some cases identical with those employed by SHM on 1987 and 1988 experimental data. Their techniques provided answers sought and illustrated results adequately. Using their methods as appropriate reduces future software development and also enables extension of the 1987 and 1988 data sets to allow more comparisons and in some cases analysis of pooled data.

For each experiment, time histories of atmospheric stability, wind, temperature, and relative humidity should be developed. Time and space histories need to be constructed of cloud-top temperature and height, cloud radar reflectivity, radiometer-measured water vapor and SLW, aircraft-measured SLW, aircraft 2D-C (and 2D-P if available) and ground-based 2D-C measured IP habits and concentrations, aircraft FSSP droplet spectra, and aircraft acoustical counter ice nuclei counts. IP characteristics of interest include habit, size, and concentration, from which estimates of the precipitation rate for each habit can be developed. The time history of precipitation at the ground should be established by the gauge network and ground-based 2D-C probe and in-cloud with the 2D probe(s). In addition, precipitation studies should include analysis of data from ultra high-resolution measurements obtained at two locations, one mobile, to enable study of events of very low precipitation rate and/or short duration (e.g., associated with a single seedline).

**2.3.2 Stability and Vertical Profiles of Temperature, Wind, and Relative Humidity.** - Knowledge of atmospheric stability and vertical profiles of temperature, wind, and relative humidity is essential to determining seeding method and targeting schemes. These quantities are obtained from rawinsonde, aircraft, and acoustic sounder data for each storm episode. Raw data can be processed with previously developed software to yield time-pressure plots of equivalent potential temperature, temperature, relative humidity, and wind. Presentation of these with coordinated time plots of precipitation, radar reflectivity, and SLW will yield important details of weather and cloud conditions. It is recommended that these plots be developed as appropriate for each experiment.

**2.3.3 Radar Reflectivity.** - The recommended C-band Doppler radar will yield space-time qualitative estimates of precipitation and quantitative estimates of cloud-top height. It also will measure the velocity of precipitation particles toward or away from radar. Techniques for developing estimates of particle velocity in 3-D space with single Doppler radar are being pursued (e.g., Wolfsberg, 1987). Should a capable and computationally efficient approach become available in the next couple of years, software should be obtained and used to estimate 3-D winds and trajectories of seeded plumes containing precipitation. Otherwise, Doppler data should be analyzed to track chaff released during aircraft seeding, thereby obtaining information on winds and plume evolvement.

Single Doppler radar can also be used to determine mesoscale phenomena, such as mesocyclones, from the analysis of volume scans (Doviak and Zrnic, 1984). Results can be displayed in figures in plan-position mode with the ordinate representing range from the radar and the abscissa representing azimuth, and arrows used to depict information about the nature of the circulation. Mesoscale circulations could affect targeting so volume scans should be made when radar time is available. Software is available for this type of analysis.

Radar data collected from volume scans of sectors should be preprocessed to yield files that are edited and reformatted for additional analysis that culminates in files of radar reflectivity factor. These files contain values of the equivalent radar reflectivity factor, $Z_e$, for each azimuth-elevation-range bin in the data grid. Further processing produces time displays of $Z_e$ in shades of gray representing intervals of intensity (fig. 2.1(a), SHM). Time plots of maximum reflectivity in the vertical can also be produced.

For each experiment in Arizona, time displays of $Z_e$ in shades of gray should be developed. These plots should then be presented with time-coordinated plots of SLW and precipitation (see figs. 2.1(b) and (c), SHM) to compare unconsumed SLW with precipitation at the ground.

### 2.3.4 Liquid Water Observations

**2.3.4.1 General comments.** - Liquid water measurements will be obtained from the vertically pointing radiometer and from aircraft instrumentation. SLW is the single most important ingredient for precipitation augmentation, so knowledge of its distribution in space and time is vital to determination of cloud seeding potential and the development of seeding strategies. It is noted that radiometer-measured SLW represents liquid water not consumed in the precipitation process taking place upwind of the ridge crest.

The radiometer can be employed in a vertical pointing or limited scanning mode. In either mode, estimates of integrated SLW include that from the lowest 600 m or so above the sensor, a zone generally not sampled by aircraft due to flight restrictions over mountainous terrain. Studies such as SHM and Rauber et al. (1986) have shown that this layer may contain significant amounts of SLW. The radiometer is generally operated continuously throughout experiments thus yielding excellent resolution in time as opposed to sampling by aircraft, which generally provide limited coverage in time due to limitations in flight logistics. However, the aircraft can provide better sampling in the horizontal plane.

The estimation of SLW from aircraft data requires more analysis than from the ground-based radiometer. Aircraft instruments used to estimate SLW are the JW hot-wire, King, and FSSP. The JW is most sensitive to droplets smaller than about 40 $\mu$m in diameter. The King is more sensitive to larger droplets. The FSSP is sensitive to smaller droplets than is the JW, but has other limitations. Some software has been developed to convert raw measurements from these instruments to engineering units and should be utilized in future Arizona experiments. Droplet spectra should be developed with the FSSP data, employing available software. Some discrepancies in SLW estimates remain. Results from airborne sensors and radiometer estimates of SLW were compared by SHM, who reported some inexplicable differences in the estimates. More study of hardware response and software development is recommended.

**2.3.4.2 Analysis of radiometer data.** - For each experiment it is recommended that time histories of radiometer-measured SLW be developed and displayed as in SHM's figure 2.1(b) to depict amount and persistence of episodes. SLW plots should be presented with those describing radar echo, cloud-top temperature (obtained from radar, rawinsonde, satellite, and aircraft measurements), acoustic sounder winds, and high-resolution precipitation to illustrate a good portion of the information needed to study seeding feasibility and strategies.

To study the climatology of SLW at ridge top, hourly averages of SLW should be developed and classified according to storm classes SS, SC, MS, and MC, for each hour of all experiments. Frequency tables and histograms by storm classes for each month of the winter season, each year with experiments, and the full sample should be prepared to illustrate the variation of SLW.

Histograms should be developed to illustrate the frequency of hourly occurrences of SLW in various concentrations during each year and for the pooled data set. Cumulative distribution plots should be constructed to illustrate percentage of total hours in each SLC amount class for the pooled sample, each season, and storm class.

To study the diurnal pattern of SLW, frequency plots of number of hours of SLW should be developed with the pooled data set and also with each year's data, for all storm classes and for each storm class. The results for the MC class should give some indication of the influence of solar heating on SLW.

Analysis by SHM indicated a relative minimum number of hours with observed SLW during 1700 to 2300 m.s.t. . A cumulative distribution plot of SLW episode duration and another by hours should be developed to depict duration histories (for example, fig. 2.2). A similar cumulative distribution plot for total SLW should be developed and compared with that for simple episode duration to determine what episode lengths are producing important amounts of SLW. This information is very important to determining seeding feasibility and strategies.

Wind roses were constructed by SHM illustrating the distribution of hours of SLW versus wind direction measured on a 70-m tower on a hill summit near Happy Jack (fig. 2.3). These and similar plots displaying amounts of SLW should be developed by year with the pooled data set and for each storm class in periods of interest. Wind roses should be developed first with all windspeeds and then with stratifications of windspeeds to further determine the conditions under which the SLW is occurring. Seeding feasibility and strategy are affected by the velocity of the passing SLW.

From the time history of SLW, wind direction, and windspeed, estimates of the SLW flux can be developed. Empirical relationships were developed by SHM to estimate the flux of SLW. The mathematical formulation they presented for a layer at mean height (z) is given as

$$F_g = SLW_z{*}V_z{*}1{,}000$$

where: $F_g$ is the flux in g/s/m crosswind
$SLW_z$ is the integrated SLW through the layer in millimeters
$V_z$ is the windspeed in m/s

The total SLW flux is the summation of the flux for all layers. To accurately estimate flux, it is necessary to know the vertical distribution of the wind in time. It was found that winds indicated at the highest layer possible by the acoustic sounder were often representative of the mean winds in the lowest 1 to 2 km a.g.l as measured by aircraft and pibals. Thus, it appears that acoustic sounder winds taken near 570 m a.g.l. (about the highest layer sampled by the sounder) generally represent actual winds over Happy Jack in the lowest 1- to 2-km layer where much of the SLW is usually available.

To estimate SLW flux in cases where clouds exceeded 2 km in depth, SHM used aircraft or rawinsonde measured winds and assumed that one-half of the integrated SLW occurred above 1 km a.g.l. Thus, two layers were employed. In MC storms, only one layer was assumed with winds as indicated by the highest level measurements taken by the acoustic sounder and SLW represented as the total integrated values obtained from radiometer measurements. The SLW flux measurements obtained by SHM appear reasonable but more data need to be obtained to verify or refine their procedure.

The distribution of SLW flux over storm duration is important to establish seeding feasibility and develop seeding strategies. Consequently, a data set needs to be developed that contains hourly flux estimates for each experiment conducted.

A cross-tabulation of SLW flux by storm type and month and also by season should be developed to continue the building of winter storms' climatology. A summary table of SLW flux estimates similar to that presented by SHM, illustrated in table 2.1, should be completed to indicate storm total flux, flux rank, etc., for each storm episode. Frequency tables and histograms of hourly flux amounts should be developed, as well as histograms of flux versus SLW amount and hours logged per SLW category also indicated.

To illustrate the potential impact of SLW flux on precipitation rate, conversion of flux should be accomplished as performed by SHM. They employed typical hourly flux amounts converted to precipitation rates assumed to occur uniformly over three downwind distances, 3, 10, and 30 km. These were selected as typical distances over which ground seeding produced precipitation is likely, given typical ice crystal growth and settling rates and typical wind velocities. Airborne seeding could lead to effects over somewhat longer distances. SHM estimated precipitation rates in reasonable agreement with gauge measurements from efficient storms. This result was expected because SLW availability sets the limits on precipitation.

Knowledge of the distribution of SLW flux with wind direction is important in Arizona experiments. This information would help determine placement of ground-seeding generators and the development of seeding aircraft flight tracks. Consequently, plots and frequency tables of flux versus wind direction should be developed.

Accurately forecasting SLW would be very useful in conducting cloud seeding. The prediction of SLW was studied by SHM through the development of simple mathematical relationships. Efforts to improve or develop new relationships for forecasting SLW should continue. Generally, the approach will be correlation analyses with expanded field data sets, followed by regression analyses on independent variables that correlate well with SLW. Some time series analyses may be useful with various variables for study of the effects of time lags. Measurements of SLW flux should be compared with model-generated precipitation estimates in studying cloud seeding potential.

### 2.3.5 Analysis of IP Measurements

**2.3.5.1 General comments.** - IP measurements will be made by a 2D-C (and possibly, a 2D-P) probe(s) mounted on an instrumented aircraft and a 2D-C probe installed on the ground near Allen Lake. The 2D-C probe has a range of 25 to 800 μm for its viewing width and a resolution of 25 μm. Sampling range for the 2D-P probe is 200 to 6400 μm and its resolution is 200 μm. The aircraft-mounted 2D-C probe has a sampling volume of about 5 L/100 m of flight and the 2D-P probe about 170 L/100 m of flight. The ground-based probe is aspirated and samples in such a way that flow equivalent is about 8 m/s.

Data from 2D-C probes are used to estimate IP habits, sizes, shapes, and concentrations, information important to determining precipitation processes. By studying the changes in these parameters before and after seeding, useful information is provided for the detection of seeding effects. Additionally, it is possible to estimate the vertical mass flux of IPs, a quantity comparable to precipitation rate.

Periodic photographing of ice crystals with a 35-mm camera located at the ground site where the 2D-C probe is located will allow comparisons of ice crystal information. This will improve the interpretation of 2D-C data.

As discussed elsewhere in this report, the ground-installed 2D-C probe can be operated throughout storm periods thus producing desirable time resolution but with the deficiency of measurement at a point. Sampling by aircraft provides information in space and importantly, for earlier phases in the growth of IPs. Consequently, it is important to view and interpret results from the two sources at least qualitatively to build more comprehensive knowledge on IPs.

**2.3.5.2 The 2D data analysis.** - The desire to estimate the vertical mass flux of IPs and investigate the formation of aggregates by computer analysis, to enable the fast and thorough processing of the substantial amounts of data generated by 2D probes, led to studies on IP shape classification by computer algorithms. With classification accomplished, a mass and terminal velocity could be assigned to each particle. Holroyd (1987) describes a technique, hereafter known as the "Holroyd technique," for processing 2D-C probe data that sorts IPs into nine classes. The procedure uses IP observables such as length, area, and perimeter, thus enabling the adaptability of the procedure to different weather and cloud regimes.

Testing of the Holroyd technique indicated it works well for most natural snowfalls. Humphries (1985) found that precipitation estimates by the Holroyd technique on ground-based 2D-C sensed IP images, collected in a variety of winter storm conditions in the Colorado mountains, were within a factor of two of gauge-measured amounts.

SHM used the Holroyd technique on data from aircraft and ground-based 2D-C probes in Arizona. In processing aircraft data collected in 1987 experiments, IP measurements were averaged over different time intervals. These included entire passes in a 10- by 15-km box about Happy Jack to deal with the substantial variability and investigate portions of in-plume and out-of-plume phases. IPs were sampled if their maximum dimension as seen by the probe exceeded 0.1 mm. The spectra of IP sizes and habits were studied in relation to their contribution to IPC and estimated precipitation rate. Concentrations were also studied to help determine plume edges.

Generally, IP measurements from the ground-positioned 2D-C probe were averaged every 15 minutes by SHM. They included in analyses only periods where estimated precipitation rates exceeded 0.1 mm/h. They tabulated only those IP habits that made a contribution to the minimum precipitation rate. The nine habits considered by the Holroyd technique are termed (1) irregular, (2) hexagonal, (3) aggregate, (4) graupel, (5) linear, (6) dendritic, (7) tiny, (8) spherical, and (9) oriented. Computer classification of habits varies some from visual observations; therefore, for studies of precipitation processes, computer results need to be carefully analyzed by scientists knowledgeable in the Holroyd technique.

Given the apparent success of the Holroyd technique, it is recommended that this method be applied in future Arizona experiments to 2D-C data collected by aircraft and on the ground and that analysis and interpretation of results be pursued along the lines followed by SHM. Particular averaging times should be determined after the data are visually inspected and flight histories are reviewed.

The histories of IPCs and sizes for each habit developed by the Holroyd technique should be analyzed for changes brought about by seeding. Analysis should consider all habits together or groups of habits depending on the variability of the measurements. Plots of the time series should be constructed with the seeded periods denoted.

It is recommended that frequency distributions of Holroyd IP habits be developed and plotted, stratified by seeded and nonseeded status. Periods considered for each plot should be individual experiments and groups of specific experiments. These show the relative prevalence of each habit and changes, if any, by seeding.

The precipitation rate for each IP habit should be computed. Time histories should be constructed for individual habits and for all habits, with seeded periods indicated.

Data from the ground-located 2D-C probe must be interpreted with substantial care as probe aspiration creates noticeable errors. Some IPs impact the sides of the aspirator hardware and break into fragments that are subsequently regarded as natural particles by the computer software. Consequently, habit and concentrations as determined by the software are erroneous to an unknown degree, as are precipitation rates calculated for each habit. However, the overall precipitation rate calculated by the software is not seriously affected. Differences between seeded and nonseeded volumes should still be evident. Comparisons to aircraft 2D-C probe results must be made with these differences in mind.

Because computer IP classifications vary some from visual observations and cannot determine if riming has occurred, it is important that periodic observations of IPs, including 35-mm photographs, be scheduled. Observations should be made at two ground locations, including the 2D-C probe location. Information gathered should include time, IP habit (including indications of riming), counts per habit, and mean size per habit.

Large IPs can account for high precipitation rates as it is important to study the effects of seeding on their distribution. Analysis of 2D-C data includes large particles to some extent but useful improvement could be made by incorporating 2D-P data. It is recommended that a technique be developed for improved study of the larger IPs if a 2D-P probe is used on the instrumented aircraft. Preferably, the analysis technique should be compatible with that developed by Holroyd for 2D-C data. While a technique such as Holroyd's is not yet available for 2D-P data, there appears to be no major obstacle to developing such a computer method.

**2.3.6 Precipitation Data Analysis.** - Knowledge of precipitation amounts in time and space is important to understanding precipitation processes in clouds and, of course, required for determining cloud seeding impacts at the ground. To adequately resolve precipitation, a number of gauges capable of measuring very small rates must be installed in the experimental area. The gauges recommended should have a resolution of 0.05 mm. Because winter precipitation rates are at times quite low, it is estimated that 10-minute totals represent the smallest consistently resolvable amounts. In one-half of the hours with detectable precipitation at their gauges on the Mogollon Rim, SHM estimated that the rate had not exceeded 0.5 mm/h.

In addition to the gauge network, it is recommended that very high-resolution precipitation data be collected at two sites (one mobile). The devices should resolve 5-minute totals when precipitation rates are very low. Results from these two devices should be incorporated with those of the gauge network.

A precipitation climatology should be constructed for each gauge location. If resources allow, histories should be developed for each gauge with 10-minute precipitation totals. As feasible, areal means should be calculated for target and control areas in each experiment. Comparisons can then be made with time histories of areal means as well as individual gauge values. The areal means will possess less variation. Hourly totals should be compared with results obtained by SHM. They developed tables that expressed some characteristics of the distribution of hourly precipitation rate.

Figures should be developed that show precipitation totals for time periods of interest such as each experimental case, month, and season. The cumulative distributions of areal mean, hourly precipitation rate for the target and control areas and for individual gauges of interest (such as that at the radiometer site), should be presented in figures. Precipitation histories for storm and cloud phases of interest should be developed. Precipitation characterizations for strata of interest such as storm or cloud class should also be developed and presented in figures and tables. These types of presentations give the general picture of precipitation. More specific analyses of precipitation are discussed in assessment of seeding effects from aircraft and ground seeding.

## 2.4 Ground Seeding Analysis

**2.4.1 General Comments.** - Seeding experiments are the most important component of future Arizona weather modification experiments. These experiments are essential to the study of the transport and diffusion of seeding agents, demonstration of the capability to deliver seeding agents to the desired volume within clouds, production and observation of seeding effects in treated clouds, and the development and demonstration of skill in targeting seeding effects to desired areas on the ground. Seeding can be conducted by ground-based or airborne ice nuclei generators. The preferred method depends on a number of factors including terrain features, atmospheric and cloud conditions, and logistics.

The efficacy of ground seeding of winter storms has been discussed by many including Super and Boe (1988), Super et al. (1988 and 1989), Grant and Rauber (1985), and Reynolds and Dennis (1986). Generally, this seeding method is considered a viable, relatively inexpensive mode to treat winter orographic clouds. The capability to conduct extended operations at any time of the day and by remote means enhances the appeal of ground seeding.

Cloud seeding by aircraft requires considerable additional equipment and personnel resources. However, studies by SHM have shown that conditions within many clouds over the Mogollon Rim dictate that cloud treatment by aircraft will be required to obtain desired seeding effects.

SHM recommended that experiments be performed with ground seeding from high elevation sites with new high-efficiency AgI solutions, as well as more conventional solutions, in high-output AgI generators. They also recommended experimentation with seeding by aircraft. Data analyses recommended in the following discussions assume experimentation with both modes of seeding.

**2.4.2 Essential Data.** - Aircraft and ground observations will be collected for each ground seeding experiment. Of particular importance is aircraft data consisting of aircraft heading and airspeed and position, atmospheric pressure, temperature, moisture, liquid water content, cloud droplet spectra, and cloud particle and ice nuclei measurements. The determination of the seeding plume can be accomplished by ice nuclei counts obtained with an acoustical counter aboard the aircraft. The acoustical counter is capable of detecting AgI plumes in clear or cloudy air. The 2D-C probe can detect sharp increases in IPs caused by seeding and thus can be used to detect a seeding plume in cloud conditions favorable to seeding creating IPs. Thus, both the acoustical counter and 2D-C probe information are used to resolve the plume.

Cloud droplet spectra developed from the aircraft FSSP probe will be used primarily in the study of IP multiplication processes. The spectra are vital to these studies.

Primary ground surface measurements in support of ground seeding experiments are windspeed and direction, temperature, precipitation, IP measurements from the ground-based 2D-C probe and 5-cm radar measurements. An instrumented tower in the experimental area will yield wind, temperature, and icing information well above tree tops. Vertical profiles of winds will be produced by the acoustic sounder. Rawinsonde measurements will be used in ground seeding analyses.

**2.4.3 Determination of Seeding Plumes.** - Initial data analysis should be aimed at determining the horizontal and vertical extent of the seeding plume. Availability of the proper computer software is crucial to performing required analyses in an efficient, largely automated manner. Case-by-case basis hand analysis requires substantial additional resources.

Habit classification software developed by Holroyd (1987) or other similar software should be applied to the archived 2D-C data set. Aircraft navigation software should be applied to aircraft data for determining position over Arizona terrain. Analysis of acoustical counter data should be accomplished similar to Super et al. (1988). Essentially, ice nuclei counts are tracked in three dimensions. The acoustical counter results should be integrated with 2D-C data analysis, to determine the AgI plume evolvement in each seeding experiment.

Computer software should be used to construct maps with seeding plume locations and pertinent wind vectors as illustrated in figure 2.4 from Holroyd et al. (1988). These diagrams present the horizontal edges of the plume and changes in time. Variability in the wind measurements is indicated by demarcation of one standard deviation from the mean of windspeed and similarly for direction. Diagrams such as these should be developed for each separate seeding plume in each experiment.

When applying a technique such as Holroyd's, vertical cross sections of plumes along selected plume axes (such as shown in fig. 2.5) should be constructed to include the pertinent profile of terrain in addition to estimates of temperature on the right ordinate of each figure. The diagrams should include demarcations of plume upper boundary, clouds, and stable layers. These figures show visually show the variability in the vertical-downwind plane of the dispersion of the seeding agent with respect to the terrain and stable layers. Temperature indications give perspective into treatment feasibility and seeding strategies.

Summary tables should contain the following for each ground seeding experiment: dates, times, seeding agent release points, identifications of map panels developed to illustrate plume boundaries and wind conditions, upper level winds, estimates of the change in potential temperature with height for key layers, cloud-top heights and temperatures, ridge-top mean temperatures, initial plume width, plume and SLW maximum heights above ridge crest, mean SLW flux over the ridge crest, predominant ice crystal types associated with seeding, estimates of mean IPCs, and precipitation rates at key levels. For each experiment, tables should also contain estimates of mean IPCs with altitude and plume width to illustrate the effect of seeding on IPCs and variability (qualitatively) of these measurements. For comparisons, tables should include estimates from measurements taken during nonseeded periods or from control areas.

It has been recommended that figures be developed that denote the outline of the plume in some horizontal and vertical planes. However, it is useful to study crosswind measurements to help determine the desirable spacing and locations of ground generators. This can be accomplished by constructing tables that give crosswind IP plume width and mean IPC for each plume at several altitudes. Other tables should show ice nuclei plume width and mean concentration at a key altitude, along with winds at several levels upwind, stability estimates from the change in equivalent potential temperature with vertical displacement, and direction of plume transport. These tables also allow comparisons of the widths of plumes of IPs and respective ice nuclei plumes.

At this point the vertical and horizontal description of the AgI plume produced by ground seeding and its dispersion and direction of movement have been accomplished to the extent the data collected allow. IP habits and respective concentrations at various locations within the cloud and at a couple of ground locations are known. By study of these results and respective weather and cloud data, seeding feasibility of each seeding agent and proper targeting strategies for ground seeding can be established. Seeding effects on cloud microphysics and on precipitation remain to be discussed.

**2.4.4 Seeding Effects on Cloud Microphysics.** - It should be shown that seeding has affected cloud microphysics and that induced changes have led to more precipitation at desired locations on the ground. Previously discussed analyses will produce the information necessary to determine microphysical changes from the seeding. Essentially, results from analyses of IP, LWC, and precipitation data will determine if changes have occurred.

Prominent seeding effects expected in comparison to natural cloud volumes are increases in IPC, compensatory decreases in SLW, and decreases in mean IP size. There should be changes in IP habits but establishing these will be difficult due to the high variability of a number of factors. These factors include whether seeding is taking place in the temperature zone where many natural crystals are forming, i.e., at −15 °C, or at warmer temperatures, where natural nucleation is much less efficient. Clearly, the temperature and liquid water structure of the cloud at the time of seeding is of importance, as is the age of the seeded volume when sampled. Nevertheless, changes in IP habits and in characteristics within each habit due to seeding should be investigated, as there may be cases with sufficient consistency for meaningful conclusions.

It is necessary to establish IPC histories for each experiment. Figures [such as fig. 2.6 adapted from Super and Heimbach (1988)] should be developed that depict aircraft-measured mean IPC versus distance from ridge top. Estimated SLW from the aircraft data also should be presented in these plots. Demarcation of seeded plume boundaries should be included.

It is expected that differences due to seeding will occur in the estimated precipitation rate obtained from analysis of the 2D data. Precipitation rate estimates and mean IPCs per individual major IP habit classification developed from aircraft 2D data should be displayed in plots such as figure 2.7, where the abscissa denotes zones of the target (seeded) and control (nonseeded) areas. Precipitation rates and mean IPCs are given by IP size and habit. Ordinate values can be averages over selected numbers of aircraft passes at a selected altitude. In these figures a substantial amount of information on IPs can be given for comparisons in detecting treatment effects.

The 2D-C data collected at the ground should be analyzed similarly to the aircraft data, with consideration that the probe is stationary and can operate continuously throughout storms. The latter fact suggests analyses of parameters in time. Time-coordinated comparisons should be made with SLW estimates from the radiometer and radar reflectivity. Figures should be developed for each experiment showing precipitation rate, IPC, and mean IP size as functions of time. These figures should indicate the time periods that are considered treated. Similar figures should be developed that make use of the habit classification information developed by the Holroyd (or similar) method. Averaging over several time periods should be employed to express fine differences to general trends. All IP habits should be plotted with treated periods indicated. Figures should be studied for changes during seeded periods.

Comparisons should be made of IP characteristics determined at ground sites by photographic and visual means during seeded periods with those during nonseeded periods. Results should be incorporated with those from the 2D-C data analysis.

**2.4.5 Seeding Effects on Precipitation.** - Establishing positive treatment effects on precipitation is the "bottom line" in future Arizona experiments. Measurements to resolve precipitation are obtained from the 2D probes, the network of gauges, and the two very high-resolution systems (one mobile).

Generally, determining seeding effects will consist of the comparison of precipitation rates over time and space for two different seeded-plume generation procedures. One procedure consists of seeding in crosswind lines that are separated by nonseeded cloud "strips." The other comprises seeding a more extensive volume by continuous orbiting aircraft or ground generator dispersal of nucleant for an hour or more. In the first procedure, precipitation comparisons will be between measurements taken from seeded and nonseeded "strips," except, occasionally, when some gauges are clearly determined to be out-of-plume and can act as additional controls. In the second procedure, comparisons will be with control measurements obtained from locations adjacent to the treated plume.

Substantial weather and cloud variability will allow only qualitative comparisons, in a statistical sense, of seeded versus nonseeded precipitation amounts in individual experiments. However, analysis of precipitation for some strata, such as all ground seeding cases, should include the application of exploratory statistical analyses if pooled sample sizes are adequate.

Provided near-average numbers of winter storms occur during the three winters of experimentation, it is expected pooling of cases will allow exploratory statistical analysis on at least three strata including all aircraft seeding events, all ground seeding events, and all seeded events. Analyses should include employment of different averaging periods in developing series to lessen noise effects.

With samples of size 15 or greater, target (seeded) versus control (nonseeded) precipitation scatter plots should be developed. The treatment effect can be estimated by the simple target/control ratio using means calculated for each area. The estimation of a P-value, where its interpretation is necessarily exploratory, should be done with statistical tests such as the multiresponse permutation procedures developed by Mielke et al. (1982). These tests do not require assumptions on the statistical distribution of precipitation.

For each experiment, precipitation gauges should be assigned as in-plume or out-of-plume. The histories of precipitation among all gauges should be compared employing cross correlation analyses that utilize time lags. Areal means for treated areas should be developed and compared with areal means for corresponding control areas.

For time periods where data exist on silver content from snow samples collected on the ground, figures should be constructed of the time series of silver content. Separate traces should be developed for individual collection sites to aid in the determination of seeded versus nonseeded status in time and space. This information can be used to corroborate other indications of seeding status.

Precipitation measurements obtained from the ground-based 2D-C probe should be compared with nearby gauges in improving the 2D-C results. Averages should be developed for treated and nontreated phases and qualitative comparisons made. Averages should be pooled for stratifications of interest and exploratory statistical analysis applied when sample sizes are adequate. In fact this approach of developing average values for individual phases of time series, can and should be applied to measurements of SLW, SLW flux, IPC, and IP mean size, along with 2D-C precipitation, and results intercompared.

Gauge-measured precipitation should be compared with radar reflectivity, SLW, SLW flux, and model-generated precipitation estimates. Comparisons should be of time series made by qualitative means. Cross correlation analyses should be performed when sample sizes are adequate. Interpretations and inferences should be formulated from these studies to cloud and precipitation processes. Implications for seeding feasibility and strategies must be determined as evidence accumulates through the experiments.

Analyses of the type discussed should be performed on high-resolution gauge data in search of a treatment signal immediately upwind and downwind of the barrier crest. Additionally, precipitation data collected in existing networks downwind of the experimental area should be analyzed by exploratory statistical methods in search of seeding effects (in cases where suitable control gauges can be identified).

## 2.5 Aircraft Seeding Analysis

Data analysis for aircraft seeding cases will proceed essentially as in ground seeding experiments. Seeding plumes must be tracked and treatment effects on IPs and precipitation must be determined. Data analyses must enable the development of targeting strategies that lead to enhanced precipitation at desired ground locations. Analyses must be adequate for determining that seeding materials can consistently be delivered to specific regions of winter storm clouds resulting in more precipitation. Data analysis should also detect negative results should they occur and the conditions that produced them.

Data analyses must determine those atmospheric and cloud conditions where ground seeding will not be productive but treatment by aircraft is feasible and likely to produce desirable results. As in ground seeding cases, the basic information is collected by the instrumented aircraft and ground-based probes. Data analyses, including the construction of the various figures and tables, are essentially the same as in ground seeding studies.

Analyses of aircraft seeding cases should establish parameter windows for temperatures, winds, cloud position and extent, and SLW profiles for specific treatment strategies. A series of aircraft treatment strategies should be developed and the applicability of each one determined. For each strategy, the type of treatment agent, dispersal rates, and preferred flight tracks should be specified.

## 2.6 Other Studies

In experiments conducted with recently developed high-yielding chemicals and ground generators located at high elevation sites, analysis of data collected will proceed in the same manner as other seeding experiments. Data analyses are required to reveal the resulting seeding plume in 3-D space, impacts on the cloud microphysics and precipitation, and the results of targeting of effects. Special attention will be given to determine whether this seeding mode can effectively treat relatively warm cases.

Determining whether the strategy of seeding throughout a storm can yield positive results on a par with those from selective seeding is an additional goal of the experiments . Data analyses to resolve this issue will generally consist of studying results from experiments with treatment of clouds that contained substantial amounts of natural ice. Special attention should be given to the SLW and precipitation profiles. An effort should be made to determine to what degree, if any, seeding clouds that contain mostly IPs is detrimental. A decision is required on whether this seeding strategy should be included in a randomized seeding program.

Experimentation must include some study of the occurrence and potential for ice multiplication in clouds that appear suitable for treatment. Ice multiplication, if it occurs to a noticeable degree and frequency, could impact seeding feasibility and strategies. The FSSP generated cloud droplet spectra should be studied for high concentrations of large droplets in cases where SLW is located in layers warmer than about $-10$ °C, conditions favorable for ice multiplication.

## 2.7 Refinement of Treatment Strategies

A number of treatment strategies in each seeding mode will be tested in experiments conducted. Some strategies will be suggested in the course of experimentation and should be subsequently researched. After completion of data analyses, classification of seeded cases and respective results should take place and a determination made of productive strategies. A study of these results along with those of area weather and climate should give a good indication of occurrence frequencies of seedable storms and thus, an indication of the feasibility of seeding over the Mogollon Rim. These results will be vital in the development of a design for a future randomized seeding program.

## 2.8 Contributions to a Randomized Program Design

Studying the results and interpretations from suggested seeding experiments will provide the information from which to develop the design of a randomized seeding program that can quantify effects more accurately both physically and statistically and provide confidence estimates for the results obtained. Results of experiments will enable the refinement of conceptual models and the development of seeding hypotheses, experimental unit declaration criteria, and statistical hypotheses. The selection of seeding agents, instrumentation and equipment, and the experimental procedures to carry out the program will be possible. There should be adequate information for the development of an assessment plan that includes specific physical and statistical evaluations. The background will also be available for generation of suspension criteria and efficient data management procedures.

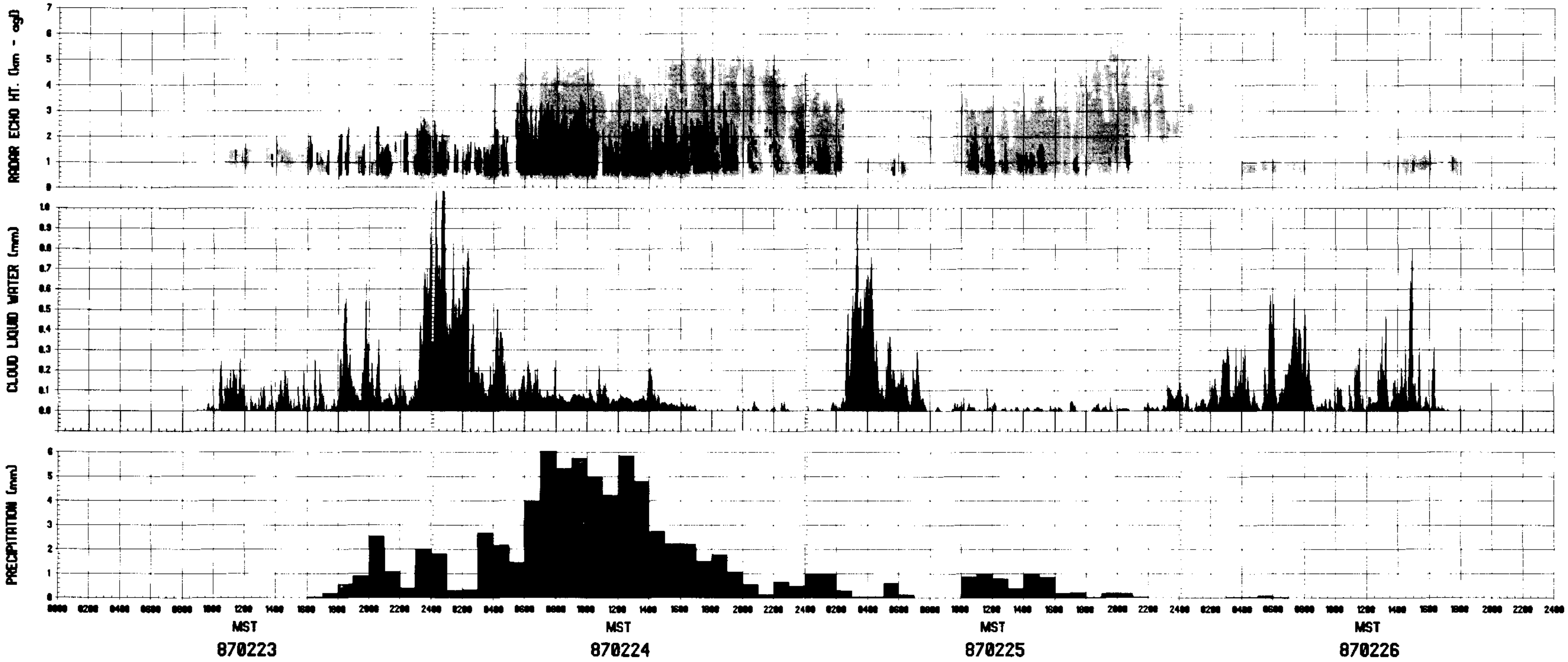

Figure 2.1. - Time history of (a) precipitation, (b) SLW, and (c) radar echos (adapted from SHM).

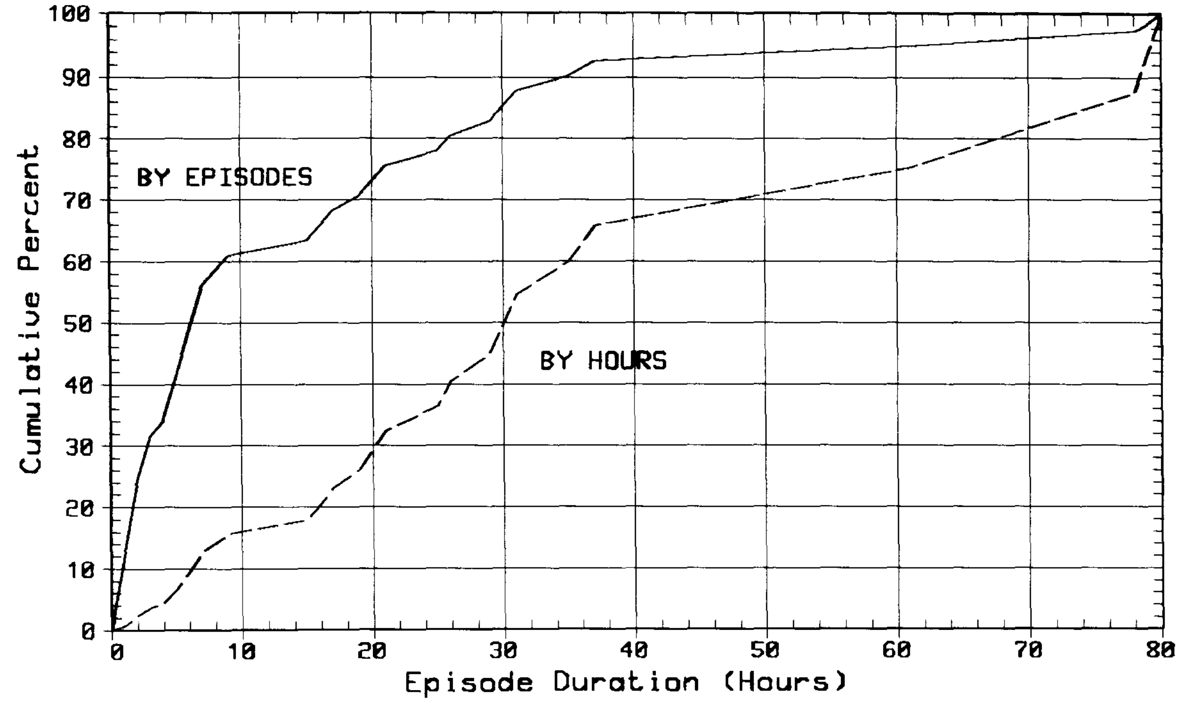

Figure 2.2. - Cumulative distributions of SLW episodes (solid line) and hours with SLW (dashed line) as functions of episode duration (from SHM).

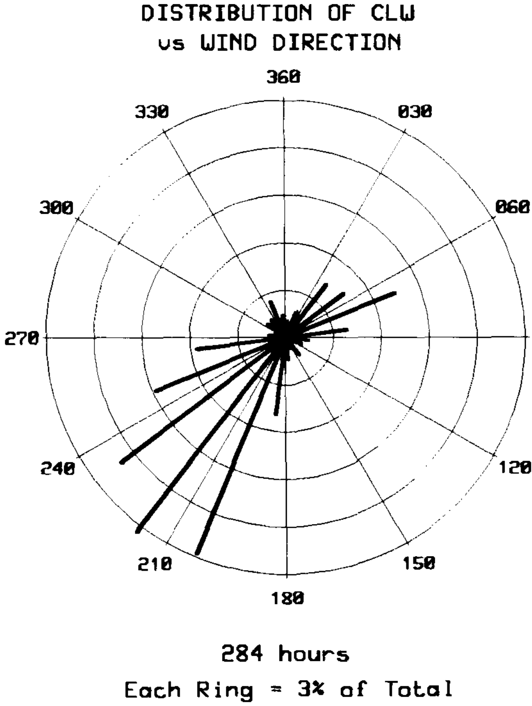

Figure 2.3. - Wind rose showing the distribution of hours with SLW versus wind direction (degrees true) for all storm classes (from SHM).

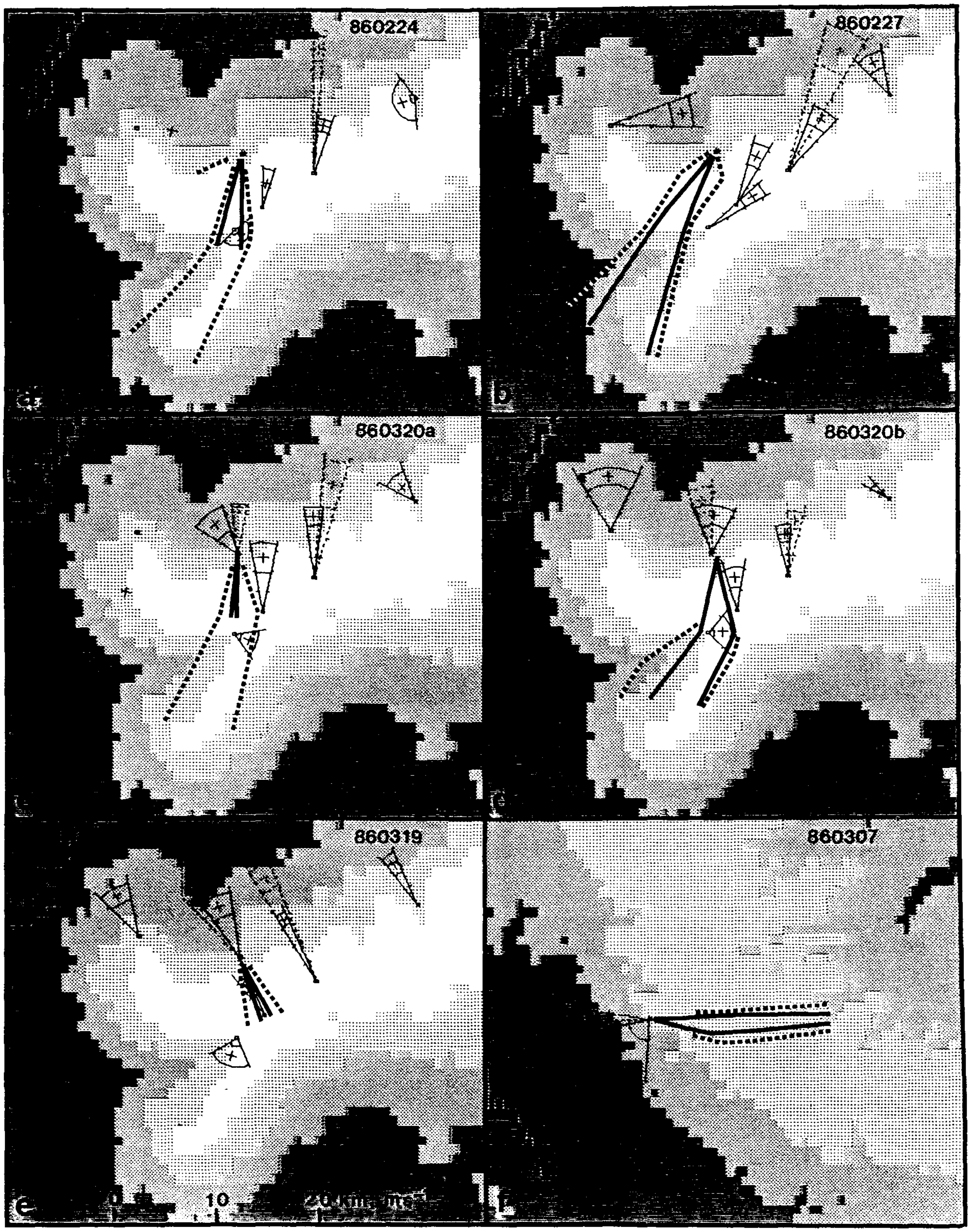

Figure 2.4. - Plume locations and wind vectors for northerly and westerly flows. The stippling in shades of gray from dark to light denote increasing terrain elevations. The bold solid and dotted lines indicate the edges of the seeding plume and its range of locations. The wedges are like arrowheads showing the direction of airflow. The crosses give the mean speeds and directions, while the arcs and radii around them represent values one standard deviation greater. The dotted wedges are for winds measured aloft at specific altitudes (from Holroyd et al., 1988).

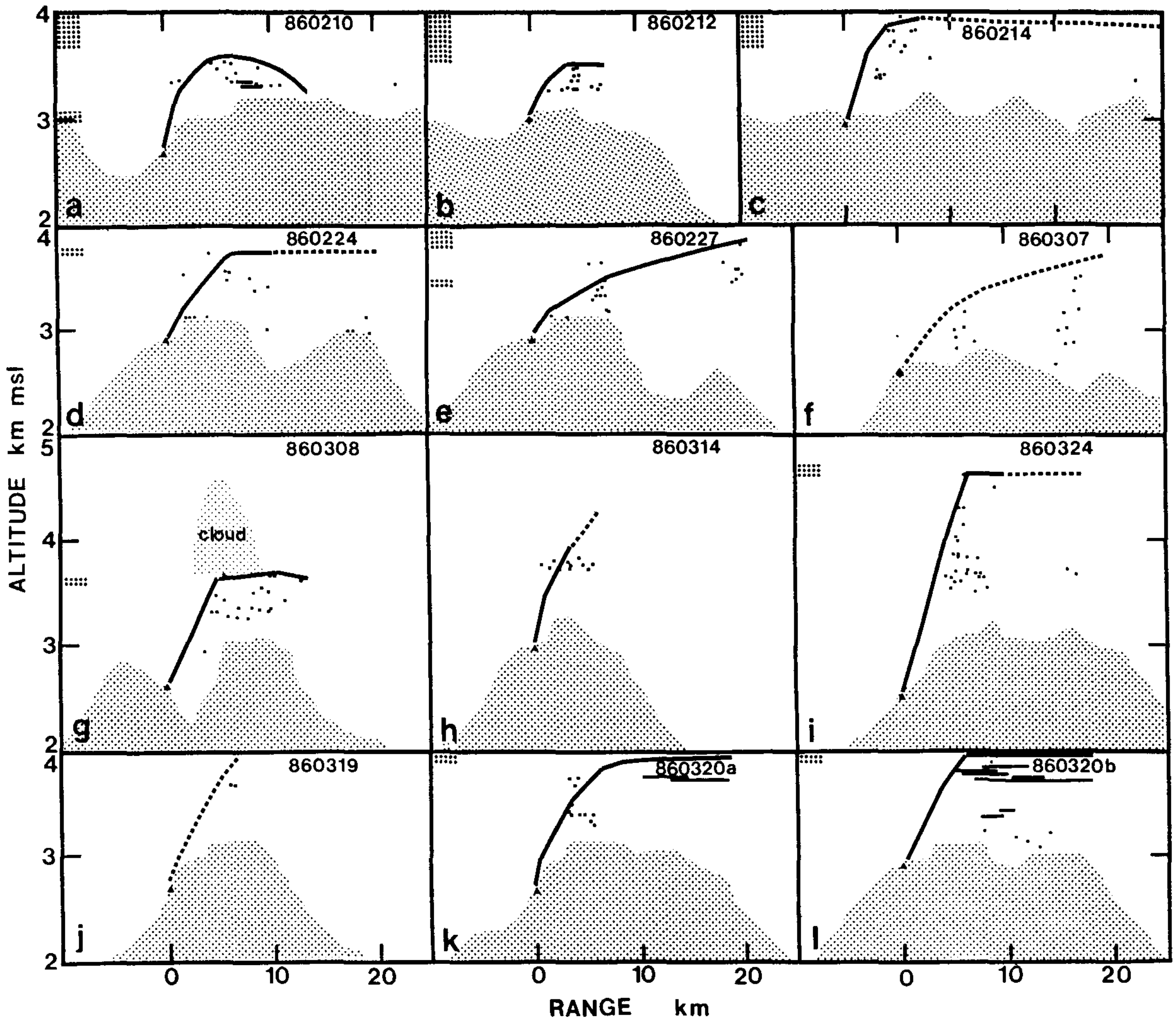

Figure 2.5. - Vertical cross sections of plumes and terrain along the axis of the plumes. The solid lines show upper plume boundaries that have been reasonably well determined. The dotted lines show approximate boundaries. The shaded rectangles at the left indicate stable layers (from Holroyd et al., 1988).

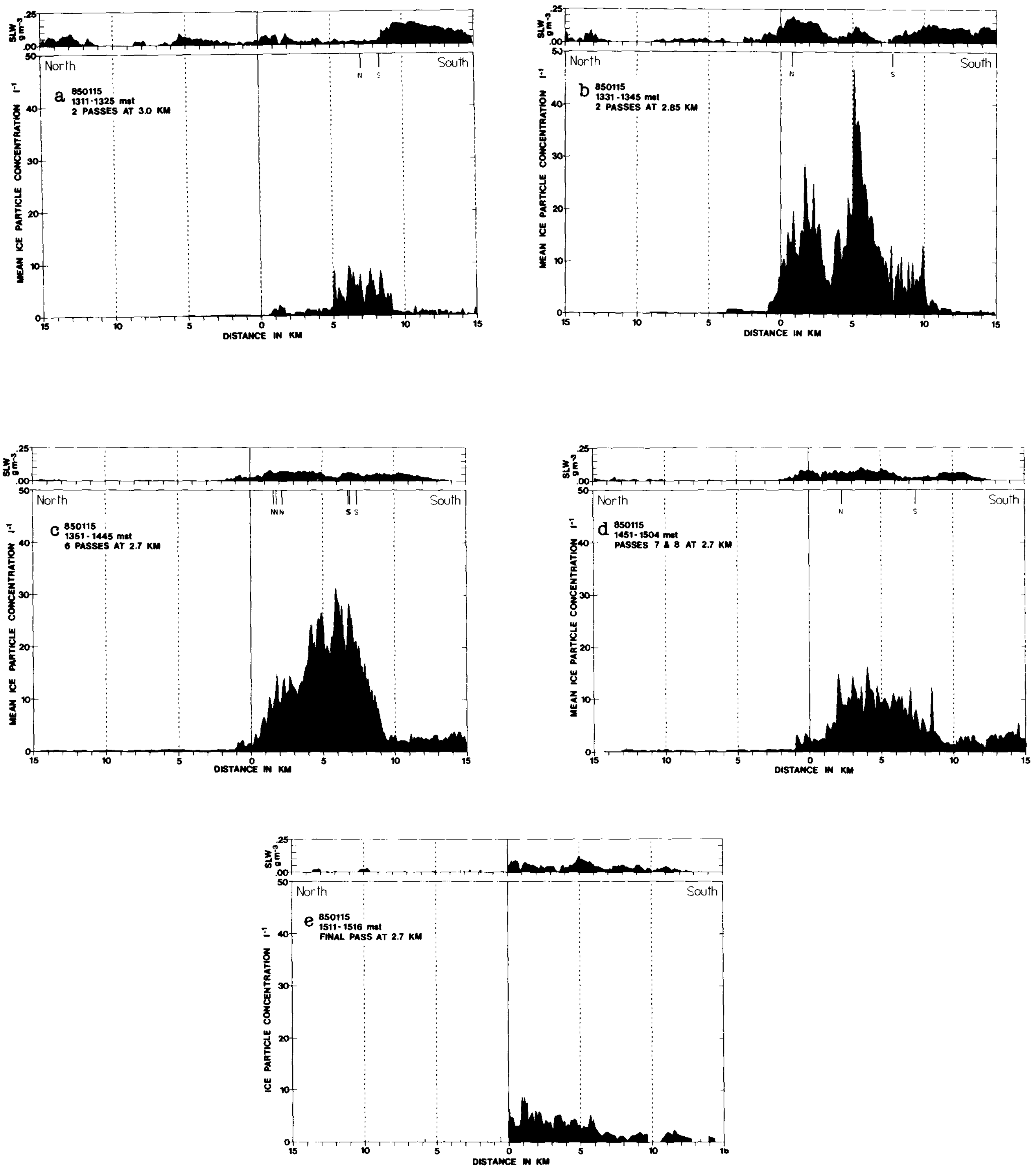

Figure 2.6. - North to south mean distributions of IPC and SLW content, with the origin 17 km east of the seeding site, for indicated numbers of passes and altitudes. The north (N) and south (S) edges of the AgI plume are shown by vertical lines at the top of each IPC plot (from Super and Heimbach, 1988).

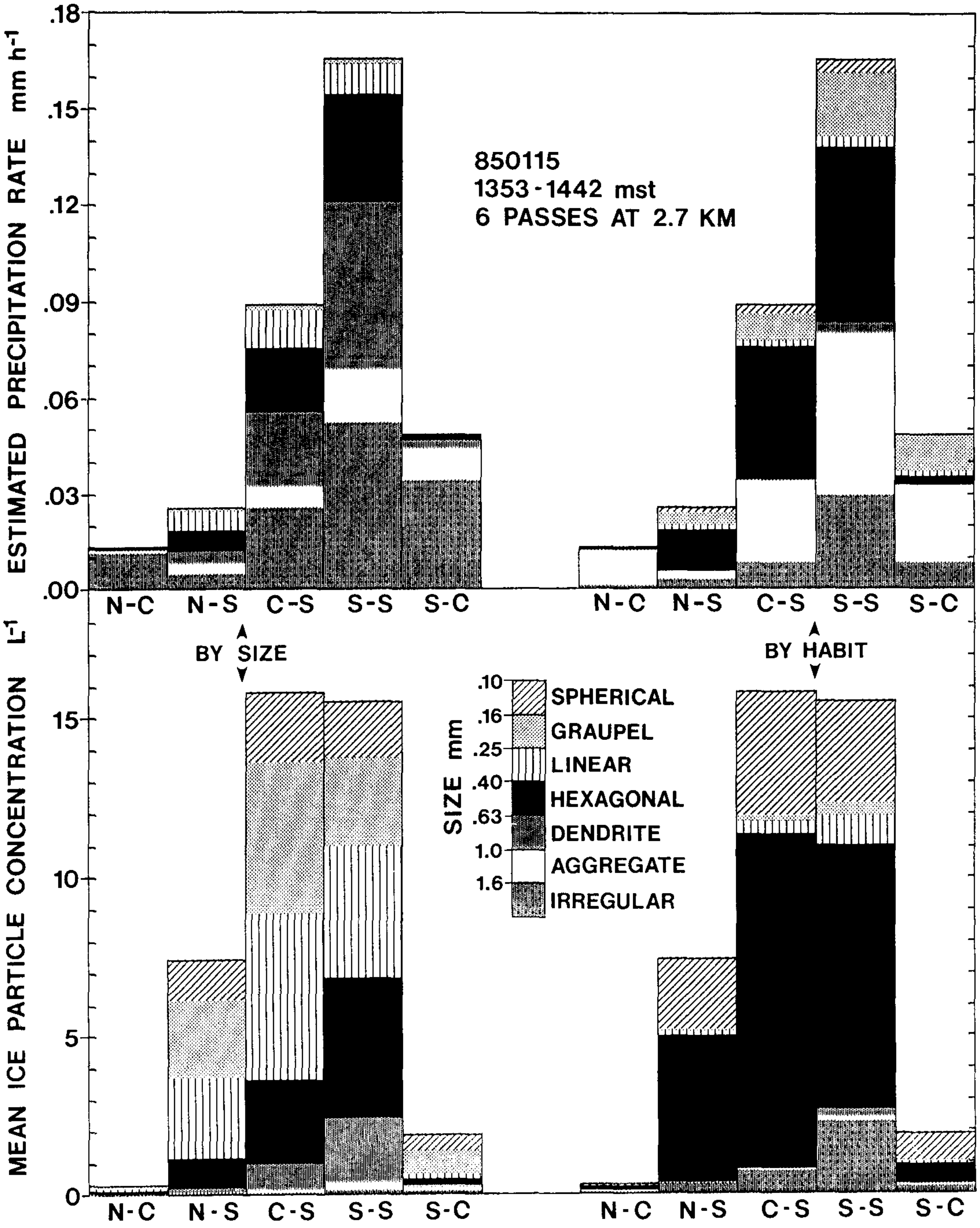

Figure 2.7. - IP concentrations and estimated precipitation rates for the seeded zone subdivided into thirds (N-C, C-S, and S-S), and north and south control zones (N-C and S-C), shown by IP size and habit. The particle size/habit shadings apply to both top and bottom panels. Values are means for the first six passes at 2.7 km (from Super and Heimbach, 1988).

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# APPENDIX

## Budget estimates for physical experiments

# CONTENTS

# BUDGET ESTIMATES FOR PHYSICAL EXPERIMENTS

## Introduction

Budget estimates for the physical cloud seeding experimental program discussed in part 1 and associated analyses described in part 2 are presented herein. The section entitled General Assumptions outlines the general assumptions that were made in the cost estimate development. The estimated program costs associated with each major task or subtask are presented in the Program Budget section. A detailed breakout of the equipment required to undertake the program is presented in the section entitled Detailed Equipment Breakout, including potential vendors for each major item. The Source List for Contracts and Equipment section contains reference vendor source lists for both equipment and contract services.

## General Assumptions

The budget estimates for the Arizona Program are based on several underlying assumptions that impact the anticipated program costs. These assumptions are summarized below:

1. Overall program management, including technical and scientific oversight, is assumed to be a State of Arizona function, although portions of this effort could be performed by other entities at the State's option. Costs are assumed to be equivalent for any option taken.

2. The field and analysis efforts are conducted through contracts with qualified groups. The three main contracts assumed are:

    a. Ground support and seeding. - This contract would provide personnel and equipment to install, operate, and maintain all ground-based equipment. In addition, this contract would provide the seeding aircraft and pilot. This arrangement would enable a single contractor to hold any necessary seeding permits, licenses, and insurance policies, and thus minimize program costs. For purposes of this budget, it is assumed that the maintenance of the seeding aircraft data system is the responsibility of the aircraft support contractor.

    b. Aircraft support. - This contract would provide an aircraft and personnel to collect all airborne cloud physics data, and to maintain the data systems for both the cloud physics and seeding aircraft.

    c. Analysis support. - This contract would provide personnel and equipment necessary to provide the scientific direction to the program and to analyze the collected data. Based on results obtained, this group would assist in the production of field operations plans for future years. They would perform comprehensive analyses of all experimental data, perform climatological analysis as described in part 2, and make recommendations concerning the design of a future randomized seeding program.

3. Equipment. - It is assumed that all major equipment items would be purchased, rather than leased, prior to the initiation of the field measurement program. This is the most cost effective alternative for a multiseason field program. Assuming the physical experiments are successful, most equipment would have direct applicability in a followup randomized seeding program aimed at demonstrating the seasonal effectiveness of seeding a large area.

4. Salaries. - A review of several recent contracts similar to those proposed for the Arizona Program reveals that a broad range of methods is used for applying indirect costs and fees to direct labor and nonlabor charges. Throughout this budget, all indirect costs and fees are assumed to be charged to direct labor only. Two rates are used to arrive at estimates of fully burdened labor cost:

a. Full-time personnel. - Fully burdened labor costs for supervisory, management, or contractor personnel who are full-time employees are calculated by multiplying the base salary by a factor of three. This translates to a total "overhead" rate of 200 percent, which is realistic for many private, university, and government groups. This broad concept of overhead includes **all** fringe benefits, such as vacation, sick leave, medical insurance, plus all indirect costs.

b. Part-time personnel. - Fully burdened labor costs for all employees hired locally on a less than 12-mo/yr basis are calculated by multiplying the base salary by a factor of two. This translates to a 100-percent total overhead rate.

5. Per diem. - This budget assumes that per diem payment is made only to full-time supervisory, management, or contractor personnel who participate in field efforts on a part-time basis. Aircrews or weather forecasters who are utilized on the project for a few months each year would be paid per diem. Personnel stationed at the project headquarters on a full-time basis and locally hired part-time employees would not receive per diem.

6. Costs. - All estimated costs are presented in terms of current 1990 dollars; that is, no inflation adjustments have been made.

7. Vendors. - The information contained in this report regarding commercial products or firms may not be used for advertising or promotional purposes and is not to be construed as an endorsement of any product or firm by Reclamation. The listed products or firms are only intended to serve as examples for budgeting purposes. No attempt has been made to provide a comprehensive vendor list for every product or service, and in all cases additional sources should be sought before purchasing or contracting arrangements are finalized.

8. Environmental assessment and monitoring costs. - This budget contains no cost estimates for any type of environmental efforts. Clearly, environmental assessments will have to be performed to implement the program and these costs will have to be considered.

## Program Budget Estimate

### Purchased Equipment. -

| | | |
|---|---|---|
| 1. | Cloud physics instrument system | $250,000 |
| 2. | Seeding aircraft instrument system | 74,000 |
| 3. | Radar set | 375,000 |
| 4. | Microwave radiometer | 310,000 |
| 5. | Doppler acoustic sounder | 65,000 |
| 6. | Instrumented tower | 35,600 |
| 7. | Ground-based 2D-C imaging system | 66,300 |

|  |  |  |  |
|---|---|---|---|
| 8. | Laser ceilometer |  | 20,000 |
| 9. | Acoustical ice nucleus counter |  | 20,000 |
| 10. | Microphotography systems (3) |  | 1,500 |
| 11. | Precipitation gauges (15) |  | 36,000 |
| 12. | Rawinsonde systems (2) |  | 173,000 |
| 13. | Ground seeding generators (4) |  | 5,000 |
| 14. | Automated weather station |  | 10,000 |
| 15. | Voice radio communications equipment |  | 39,500 |
| 16. | Data radio communications equipment |  | 25,000 |
| 17. | Cold room snow sampling stations |  | 54,000 |
| 18. | (OPTIONAL) Remote seeding generator system (12) |  | 154,000 |
| TOTAL PURCHASED EQUIPMENT |  | MINIMUM | $1,559,900 |
|  |  | OPTIONAL | $1,713,900 |

**Program Management and Direction (Annual Costs). -**

| *A. Personnel* | *No. months* | *$/month (base)* | *$/month (burdened)* | *$ total cost (burdened)* |
|---|---|---|---|---|
| 1. Program Manager | 12 | 4,250 | 12,750 | 153,000 |
| 2. Contract specialist | 6 | 2,500 | 7,500 | 45,000 |
| 3. Advisory panel (3 persons) | 3 | 4,250 | 12,750 | 38,250 |
| 4. Per diem (3 persons) (advisory panel) | 30 d @$78/d |  |  | 7,020 |
| 5. Travel |  |  |  | 3,000 |
|  |  |  | TOTAL: | $246,270 |

**Annual Cost of Contract for Ground Support and Seeding**

**Field direction, technical staff. -**

| *A. Personnel* | *No. months* | *$/month (base)* | *$/month (burdened)* | *$ total cost (burdened)* |
|---|---|---|---|---|
| 1. Principal investigator (contract supervision) | 1 | 4,500 | 13,500 | 13,500 |
| 2. Field coordinator (FC) | 12 | 4,250 | 12,750 | 153,000 |
| 3. Forecaster/assistant FC | 4 | 3,000 | 9,000 | 36,000 |
| 4. Electronics technician | 12 | 3,000 | 9,000 | 108,000 |
| 5. Chief field technician | 12 | 2,500 | 7,500 | 90,000 |
| 6. Secretary | 12 | 1,350 | 4,050 | 48,600 |
| Per diem (1 person) (forecaster) | 120 d @$66/day |  |  | 7,920 |

*B. Transportation*

1. 4-WD trucks (3)

| | | |
|---|---|---|
| Lease charges | 36 mo @$350/mo | 12,600 |
| Mileage charges | 30,000 mi @$0.30/mi | 9,000 |

*C. Support facilities; services and supplies*

| | |
|---|---|
| 1. Office and warehouse rental | 50,000 |
| 2. Communications, office supplies, etc. | 12,000 |
| 3. Miscellaneous supplies and services | 15,000 |
| 4. Insurance against consequential effects of cloud seeding insurance | 5,000 |
| **Subtotal:** | $560,620 |

**Precipitation gauge, ground seeding, snow sample collection, and microphotograph operations. -**

| *A. Personnel* | *No. months* | *$/month (base)* | *$/month (burdened)* | *$ total cost (burdened)* |
|---|---|---|---|---|
| 1. Technician | 4 | 1,350 | 2,700 | 10,800 |
| 2. Technician | 4 | 1,350 | 2,700 | 10,800 |
| 3. Technician | 4 | 1,350 | 2,700 | 10,800 |
| 4. Technician | 4 | 1,350 | 2,700 | 10,800 |

*B. Transportation*

1. 4-WD trucks (2)

| | | |
|---|---|---|
| Lease charges | 8 mo @$350/mo | 2,800 |
| Mileage charges | 8,000 mi @$0.30/mi | 2,400 |

2. Helicopter

| | | |
|---|---|---|
| Flight time | 20 h @$400/h | 8,000 |

3. Snowmobiles (2)

| | | |
|---|---|---|
| Lease charges | 8 mo @$500/mo | 4,000 |
| Operating expenses | 8 mo @$100/mo | 800 |

| | | |
|---|---|---|
| *C. Supplies* | | |
| Precipitation gauge operations | | |
| 1. Antifreeze | | 1,250 |
| 2. Charts, ink, spare clocks | | 750 |
| Seeding generators operations | | |
| 1. AgI solution | | 3,000 |
| 2. Fuel and tank rental | | 400 |
| 3. Parts and maintenance | | 300 |
| Microphotographs | | |
| 1. Film and developing | | 600 |
| 2. Snow sampling materials | | 500 |
| *D. Services* | | |
| 1. Silver-in-snow analysis | 1,000 samples @ $100/sample | 100,000 |
| 2. Utilities (2 sampling sites) | | 600 |
| | **Subtotal:** | $168,000 |

**Rawinsonde operations. -**

| *A. Personnel* | *No. months* | *$/month (base)* | *$/month (burdened)* | *$ total cost (burdened)* |
|---|---|---|---|---|
| 1. Technician (Camp Verde) | 4 | 1,350 | 2,700 | 10,800 |
| 2. Technician (Allen Lake) | 4 | 1,350 | 2,700 | 10,800 |
| *B. Transportation* | | | | |
| 1. Technician's personal vehicle mileage allowance | 3,000 mi @$0.25/mi | | | 750 |
| *C. Supplies* | | | | |
| 1. Rawinsonde sets | 240 sets @$100/set | | | 24,000 |
| 2. Helium | 80 tanks @$60/tank | | | 4,800 |
| 3. Parts and maintenance | | | | 2,000 |
| 4. Site expenses - rent and utilities | | | | 2,000 |
| | | | **Subtotal:** | $55,150 |

**Mormon Lake operations center operations. -**

| *A. Personnel* | *No. months* | *$/month (base)* | *$/month (burdened)* | *$ total cost (burdened)* |
|---|---|---|---|---|
| 1. Technician | 4 | 1,750 | 3,500 | 14,000 |
| *B. Transportation* | | | | |
| 1. 4-WD truck (1) | | | | |
| Lease charges (monthly) | 4 mo @$350/mo | | | 1,400 |
| Mileage charges | 4,000 mi @$0.30/mi | | | 1,200 |
| *C. Supplies* | | | | |
| 1. Supplies | | | | 2,000 |
| 2. Parts and maintenance | | | | 10,000 |
| *D. Services* | | | | |
| 1. Utilities | | | | 2,000 |
| 2. Weather forecast (maps, satellite, etc.) | | | | 25,000 |
| | | | **Subtotal:** | $55,100 |

**Allen Lake field site operations. -**

| *A. Personnel* | *No. months* | *$/month (base)* | *$/month (burdened)* | *$ total cost (burdened)* |
|---|---|---|---|---|
| 1. Technician | 4 | 1,750 | 3,500 | 14,000 |
| *B. Transportation* | | | | |
| 1. 4-WD truck (1) | | | | |
| Lease charges (monthly) | 4 mo @$350/mo | | | 1,400 |
| Mileage charges | 4,000 mi @$0.30/mi | | | 1,200 |
| *C. Supplies* | | | | |
| 1. Supplies | | | | 2,000 |
| 2. Parts and maintenance | | | | 10,000 |
| *D. Services* | | | | |
| 1. Utilities | | | | 1,500 |
| | | | **Subtotal:** | $30,100 |

**Seeding aircraft operations. -**

| A. *Personnel* | *No. months* | *$/month (base)* | *$/month (burdened)* | *$ total cost (burdened)* |
|---|---|---|---|---|
| 1. Pilot | 3.5 | 3,000 | 9,000 | 31,500 |
| 2. Per diem (1 person) | 90 d @$78/day | | | 7,020 |
| B. Aircraft (twin engine) | | | | |
| Lease cost | 4 mo @$4,000/mo | | | 16,000 |
| Flight time | 120 h @ $150/h | | | 18,000 |
| Equipment installation/removal | | | | 4,000 |
| Spare parts | | | | 1,000 |
| | | | **Subtotal:** | $77,520 |

**OPTION - Remote ground generator network operations. -**

| A. *Personnel* | *No. months* | *$/month (base)* | *$/month (burdened)* | *$ total cost (burdened)* |
|---|---|---|---|---|
| 1. Electronics technician | 5 | 2,500 | 5,000 | 25,000 |
| 2. Technician | 5 | 1,350 | 2,700 | 13,500 |
| B. *Transportation* | | | | |
| 1. 4-WD trucks (1) | 4 mo @$4,000/mo | | | 16,000 |
| Lease charges | 5 mo @$350/mo | | | 1,750 |
| Mileage charges | 8,000 mi @$0.30/mi | | | 2,400 |
| 2. Helicopter remote seeding (hourly) | 40 h @$400/h | | | 16,000 |
| C. *Supplies* | | | | |
| Seeding generator operations | | | | |
| 1. AgI solution | | | | 9,000 |
| 2. Fuel and tank rental | | | | 5,000 |
| 3. Parts and maintenance | | | | 3,000 |
| | | | **Subtotal:** | $75,650 |
| | | | **TOTAL:** | $947,090 |
| Initial operations including remote ground seeding: | | | | $1,022,740 |

## Annual Cost of Aircraft Support Contract. -

### Cloud Physics Aircraft. -

| *A. Personnel* | *No. months* | *$/month (base)* | *$/month (burdened)* | *$ total cost (burdened)* |
|---|---|---|---|---|
| 1. Principal investigator | 1 | 4,000 | 12,000 | 12,000 |
| 2. Flight scientist | 3.5 | 3,500 | 10,500 | 36,750 |
| 3. Pilot | 3.5 | 3,000 | 9,000 | 31,500 |
| 4. Electronics technician | 4 | 2,500 | 7,500 | 30,000 |
| 5. Per diem (3 persons) | 90 d @$78/d | | | 21,060 |
| *B. Aircraft (King Air series or equal)* | | | | |
| Lease cost | 4 mo @$8,000/mo | | | 32,000 |
| Flight time | 120 h @$300/h | | | 36,000 |
| Equipment installation/removal | | | | 10,000 |
| Spare parts | | | | 5,000 |
| | | | TOTAL: | $214,310 |

## Annual Cost of Analysis Contract. -

| *A. Personnel* | *No. months* | *$/month (base)* | *$/month (burdened)* | *$ total cost (burdened)* |
|---|---|---|---|---|
| 1. Chief scientist/analyst | 12 | 5,000 | 15,000 | 180,000 |
| 2. Analyst | 12 | 4,250 | 12,750 | 153,000 |
| 3. Analyst | 12 | 4,250 | 12,750 | 153,000 |
| 4. Programmer | 12 | 3,500 | 10,500 | 126,000 |
| 5. Secretary | 12 | 1,350 | 4,050 | 48,600 |
| *B. Office rental with utilities* | | | | 25,000 |
| *C. Supplies* | | | | 10,000 |
| *D. Computer system charges* | | | | 25,000 |
| | | | TOTAL: | $720,600 |

### Estimated 5-year Program Cost. -

Shown below is the estimated cost for a minimum length (5-year) program. This assumes that contracts are established and most equipment purchased in the initial year. During years 2, 3, and 4, field measurement and analysis efforts are carried out simultaneously, with a remote ground seeding generator network being utilized in the latter 2 years. The analysis effort would culminate in the fifth year with the development of a demonstration phase plan.

Other alternatives are certainly possible. For example, the same program could be conducted over an 8-year period at slightly increased total cost if field and analysis efforts were carried out on alternate years.

**Estimated costs in 1990 dollars**

| Budget category | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 |
|---|---|---|---|---|---|
| Equipment | $1,559,900 | | $154,000 | | |
| Management | 246,270 | 246,270 | 246,270 | 246,270 | 246,270 |
| Ground support | | 947,090 | 1,022,740 | 1,022,740 | |
| Aircraft support | | 214,310 | 214,310 | 214,310 | |
| Analysis | | 720,600 | 720,600 | 720,600 | 720,600 |
| Annual cost | $1,806,170 | $2,128,270 | $2,357,920 | $2,203,920 | $966,870 |
| Total program cost in 1990 dollars | | | | | $9,463,150 |

## Detailed Equipment Breakout

A large variety of specialized equipment will be required to conduct the program. Each major system or item required is identified below, along with a current estimated cost and a representative supplier or manufacturer. A comprehensive market survey encompassing all potential suppliers for each item has not been made, so prices quoted must be considered only representative.

**Cloud Physics Aircraft Instrument System. -** It will be more cost effective to purchase and assemble a cloud physics instrument system than to lease a fully equipped aircraft. Two well instrumented aircraft are known to be potentially available. These are owned and operated by the University of Wyoming and the University of North Dakota. The latter provided a cost estimate for utilization of their aircraft of from $140,000 to $200,000 per month. This included 40 flight hours per month, all crew, and ground computer support necessary to produce an archive data set. Thus, for a 3-month program the minimum cost would be approximately $420,000. Inspection of the budget estimates that follow will indicate that the most cost effective alternative is to purchase and assemble an instrument system, and lease an aircraft to carry the system and collect the data.

Instrument system component and assembly costs.

| | |
|---|---|
| 1. PMS 2D2-C optical array probe | $38,500 |
| 2. PMS 2D2-P optical array probe | 41,000 |
| 3. PMS FSSP-100 forward scattering spectrometer | 25,000 |
| 4. PMS King liquid water content probe | 8,000 |
| 5. Cloud Technology J-W liquid water probe | 5,000 |
| 6. Static pressure sensor | 2,000 |
| 7. Dynamic pressure sensor | 2,000 |

| | | | |
|---|---|---|---|
| 8. | King KLN88 Loran navigation system | | 4,500 |
| 9. | Rosemount total temperature probe | | 2,000 |
| 10. | General Eastern 1011 dewpoint system | | 10,000 |
| 11. | King KRA405 radar altimeter system | | 11,000 |
| 12. | Power inverters, Avionics Instruments, Inc. 2 each PL200-2a units | | 15,000 |
| 13. | Heated pitot system | | 500 |
| 14. | Static ports, 2 each | | 500 |
| 15. | Acoustical ice nucleus counter | | 20,000 |
| 16. | Video camera and recorder | | 3,000 |
| 17. | SEA data acquisition system | | |
| | a. Model 200 CPU (80386) | | 6,800 |
| | b. 2000 Mbyte Exabyte tape drive | | 5,300 |
| | c. Princeton HX-12E EGA color monitor | | 700 |
| | d. Dai-Ichi 7-inch EGA monitor | | 2,200 |
| | e. PMS FSSP interface | | 2,800 |
| | f. PMS 2D probe interfaces, 2 each | | 9,000 |
| | g. Analog input system card | | 4,600 |
| | h. Digital input/output card | | 1,400 |
| | i. Loran interface | | 2,500 |
| | j. Acquisition software | | 4,400 |
| 18. | Parts and materials for system assembly | | 5,000 |
| 19. | Labor for system assembly and bench test | | |
| | a. Elec. Engineer | 80 h @ $24 x 3 (OH) | 5,760 |
| | b. Elec. Tech | 120 h @ $12 x 3 (OH) | 4,320 |
| | c. Tech. | 120 h @ $ 8 x 3 (OH) | 2,880 |
| 20. | Spare parts | | 4,340 |
| | Total estimated system cost | | $250,000 |

**Seeding Aircraft Instrument and Equipment Package. -**

| | | |
|---|---|---|
| 1. | Aero Systems, Inc. E-16 acetone seeding generator | $6,000 |
| 2. | Cloud Technology J-W liquid water probe | 5,000 |
| 3. | Static pressure sensor | 2,000 |
| 4. | Dynamic pressure sensor | 2,000 |
| 5. | King KLN88 loran navigation system | 4,500 |
| 6. | Rosemount total temperature probe | 2,000 |
| 7. | General Eastern 1011 dewpoint system | 10,000 |
| 8. | Power inverter, Avionics Instruments, Inc. 2A100-1G | 4,000 |
| 9. | Heated pitot system | 500 |
| 10. | Static ports, 2 each | 500 |
| 11. | Video camera and recorder | 3,000 |
| 12. | Radar chaff dispenser, Atmospherics, Inc. | 6,000 |
| 13. | Seeding generator flame temperature monitor | 500 |
| 14. | SEA data acquisition system | |
| | a. Model 200 CPU (80286) | 5,200 |
| | b. NEC Multisync II EGA color monitor | 900 |
| | c. Analog input system card | 4,600 |
| | d. Loran interface | 2,500 |
| | e. Acquisition software | 4,400 |
| 15. | Parts and materials for system assembly | 2,500 |
| 16. | Labor for system assembly and bench test | 5,000 |
| 17. | Spare parts | 2,900 |
| | Total estimated system cost | $74,000 |

### Radar System. -

| | | |
|---|---|---|
| 1. | Enterprise Electronics, Inc. DWSW-88 radar set | $350,000 |
| 2. | Trailer for radar and other equipment at Mormon Lake Operations Center | 25,000 |
| | Total estimated system cost | $375,000 |

### Microwave Radiometer System(s). -

One or two systems are contemplated depending on price. Existing sources (DRI or NOAA) could provide one unit for this price, while two units could be obtained from a firm (Ophir) that has recently developed a different type of radiometer, if their unit passes field tests.

| | | |
|---|---|---|
| 1. | Radiometer unit(s) | $300,000 |
| 2. | Trailer for radiometer and other equipment at Allen Lake | 10,000 |
| | Total estimated system cost | $310,000 |

### Doppler Acoustic Sounder: AeroVironment, Inc. -

$65,000

### Allen Lake Instrumented Tower. -

| | | |
|---|---|---|
| 1. | Wind sensors: Hydrotech, Inc. | $4,000 |
| 2. | Temperature/humidity sensor: Vaisala HM32 | 1,600 |
| 3. | Icing events: Rosemount | 3,000 |
| 4. | Nondirectional aircraft navigation beacon Aviation Systems, Inc. (with installation) | 22,000 |
| 5. | Tower, 100-foot: Weathermeasure, Inc. | 3,600 |
| | Tower erection | 1,400 |
| | Total estimated system cost | $35,600 |

### Ground-Aspirated IP Imaging System. -

| | | |
|---|---|---|
| 1. | PMS 2D2-C optical array probe | $38,500 |
| 2. | PMS PDS-400 data acquisition system | 15,000 |
| 3. | PMS printer/plotter | 2,800 |
| 4. | PMS aspirator unit | 5,000 |
| 5. | Instrument shelter | 5,000 |
| | Total estimated system cost | $66,300 |

### Laser Ceilometer: Vaisala, Inc. CT-12K. -

$20,000

### Acoustical Ice Nucleus Counter. -

$20,000

### Microphotography System, Three Sites. -

$1,500

### Precipitation Gauge Network. -

| | | |
|---|---|---|
| 1. | Precipitation gauges: Belfort 5-780, 12 each | $21,000 |
| 2. | Gauge stand, custom shroud, custom bucket, Alter shield, spare chart drives: 15 sets | 15,000 |
| | Total estimated system cost | $36,000 |

**Rawinsonde Systems. -**

| | | |
|---|---|---|
| 1. | Radiosonde receiver/tracking systems, AIR,Inc. Model IS-4A1-UAS-120-MD1, 2 each | $160,000 |
| 2. | Instrument shelters, portable, 2 each | 10,000 |
| 3. | Video camera and recorder (Camp Verde) | 3,000 |
| | Total estimated system cost | $173,000 |

**Portable Ground Seeding Generators, 4 each. -** $5,000

**Automated Weather Station (Crooks Trail Road), Handar, Inc. -** $10,000

**Voice Radio Communications System (GE or Motorola). -**

| | | |
|---|---|---|
| 1. | Base radios with antennas and power supplies, 7 each | $10,500 |
| 2. | Mobile radios with antennas (truck and aircraft units), 8 each | 8,000 |
| 3. | Portable radios, hand-held, 4 each | 4,000 |
| 4. | Repeater stations, 2 each | 12,000 |
| 5. | Installation of radios by supplier | |
| | a. Base and mobile units, 15 each | 3,000 |
| | b. Repeaters, 2 each | 2,000 |
| | Total estimated system cost | $39,500 |

**Data Radio Communications System. -** Used to transfer current data to the Mormon Lake Operations Center.

| | | |
|---|---|---|
| 1. | 386 series PCs for data collection, processing, display and storage, 2 sites | $10,000 |
| 2. | X.25 radio data transmitters/receivers with antennas, band pass filters, 3 sites | 9,000 |
| 3. | X.25 repeaters, 2 sites | 6,000 |
| | Total estimated system cost | $25,000 |

**Cold Rooms for Silver-in-Snow Sample Collection and IP Microphotography. -**

| | | |
|---|---|---|
| 1. | Walk-in cooler units, 3 sites | $24,000 |
| 2. | Custom trailers for above | 21,000 |
| 3. | High resolution precipitation monitors, 3 each | 9,000 |
| | Total estimated system cost | $54,000 |

**Remote Seeding Generator Network. -** This network will be required only if the initial experiments indicate that ground seeding will be a viable option for Arizona conditions.

| | | |
|---|---|---|
| 1. | Master seeding control station | $22,000 |
| 2. | Remote generator units, 12 each | 60,000 |
| 3. | Radio repeater stations, 2 each | 6,000 |
| | Total estimated system cost | $154,000 |

## Source List for Contracts and Equipment

### Contract Source List. -

Listed below are potential vendors to provide the necessary contracted services.

**Cloud physics and seeding aircraft instrument and data system package design, procurement, fabrication, and bench testing. -**

Aero Systems, Inc.
2580 South Main
Erie CO 80516
(303) 665-9321

Atmospherics, Inc.
5652 East Dayton Ave.
Fresno CA 93727
(209) 291-5575

Colorado International Corp.
PO Box 3007
Boulder CO 80307
(303) 443-0384

North American Weather Consultants
3761 South 700 East
Salt Lake City UT 84106
(801) 263-3500

Science Engineering Associates.
PO Box 115
South Willington CT 06265
(203) 487-1869

Weather Modification, Inc.
PO Box 198
Bowman ND 58623
(701) 523-5606

**Ground field support. -**

Atmospherics, Inc.
5652 East Dayton Ave.
Fresno CA 93727
(209) 291-5575

Colorado International Corp.
PO Box 3007
Boulder CO 80307
(303) 443-0384

North American Weather Consultants
3761 South 700 East
Salt Lake City UT 84106
(801) 263-3500

**Aircraft support. -**

Aero Systems, Inc.
2580 South Main
Erie CO 80516
(303) 665-9321

Atmospherics, Inc.
5652 East Dayton Ave.
Fresno CA 93727
(209) 291-5575

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Salt Lake City UT 84106
(801) 263-3500

Weather Modification, Inc.
PO Box 198
Bowman ND 58623
(701) 523-5606

**Equipment and services source list. -**

Included below are names and addresses of representative vendors for all major items. The user is cautioned that this listing is not all-inclusive, and that efforts should be made to identify alternate sources.

| Vendor | Type of service or equipment |
|---|---|
| Aero Systems, Inc.<br>2580 South Main<br>Erie CO 80515<br>(303) 665-9321 | Aircraft data systems, aircraft contract services, aircraft seeding generators |
| AeroVironment, Inc.<br>825 Myrtle Ave.<br>Monrovia CA 91016-3424<br>(818) 357-9983 | Doppler acoustic sounding systems |
| Atmospheric Instrumentation Research, Inc. (AIR)<br>8401 Baseline Road<br>Boulder CO 80303<br>(303) 499-1701 | Upper air sounding systems, pressure sensors |
| Atmospherics, Inc.<br>5652 East Dayton Ave.<br>Fresno CA 93727<br>(209) 291-5575 | Aircraft data systems, aircraft contract services, contract field services, aircraft radar chaff systems |
| Aviation Insurance Assoc.<br>PO Box 3506<br>Rapid City SD 57709<br>1-800-338-3856 | Weather modification insurance |
| Belfort Instrument Co.<br>727 Wolfe Street<br>Baltimore MD 21231<br>(301) 342-2626 | Precipitation gauges, general meteorological equipment. |
| Bendix/King Avionics<br>General Aviation Division<br>400 North Rogers Road<br>Olathe KS 66062<br>(913) 782-0400 | Aircraft navigation and communication equipment |
| Cloud Technology<br>606 Wellsbury Court<br>Palo Alto CA 94306<br>(415) 797-6498 | Aircraft liquid water content sensors (J-W) |
| Colorado International Corp.<br>P.O. Box 3007<br>Boulder CO 80307<br>(303) 443-0384 | Aircraft data systems, aircraft contract services, contract field services. |

| | |
|---|---|
| Deepwater Chemical Corp.<br>PO Box 171599<br>Irvine CA 92713<br>(714) 751-3522 | Cloud seeding chemicals |
| Desert Research Institute<br>Atmospheric Sciences Center<br>PO Box 60220<br>Reno NV 89506<br>(702) 673-7300 | Silver-in-snow analysis, microwave radiometers. |
| EG&G<br>151 Bear Hill Road<br>Waltham MA 02154 | Temperature/dewpoint sensors, general meteorological equipment |
| Enterprise Electronics Corp.<br>PO Box 1216<br>Enterprise AL 36331-1216<br>(205) 347-3478 | Weather radar systems |
| General Eastern Instruments Corp.<br>50 Hunt Street<br>Watertown MA 02172<br>(617) 923-2386 | Hygrometers and dewpoint measuring systems |
| Handar, Inc.<br>1188 Bordeaux Drive<br>Sunnyvale CA 94089<br>(408) 734-9640 | Meteorological and environmental monitoring equipment, automatic weather stations |
| Hydro-Tech<br>4658 NE. 178th Street<br>Seattle WA 98155<br>(206) 362-1074 | Deiced wind measuring systems |
| Dr. Gerhard Langer<br>3995 Carlock<br>Boulder CO 80303<br>(303) 494-7012 | Acoustical ice nuclei counter fabrication |
| North American Weather Consultants<br>3761 South 700 East<br>Salt Lake City UT 84106<br>(801) 263-3500 | Aircraft data systems, aircraft contract services, contract field services |
| Ophir Corp.<br>3190 South Wadsworth Blvd.<br>Lakewood CO 80226<br>(303) 986-1512 | Microwave radiometers |

| | |
|---|---|
| NOAA<br>Environmental Research Labs<br>325 Broadway<br>Boulder CO 80303<br>(303) 497-3000 | Microwave radiometers |
| Particle Measuring Systems, Inc. (PMS)<br>1855 South 57th Court<br>Boulder CO 80301<br>(303) 443-7100 | Aircraft optical array probes, liquid water content meters, and data acquisition systems |
| Rosemount, Inc.<br>Box 959<br>14300 Judicial Road<br>Burnsville MN 55337<br>(612) 435-4300 | Aircraft temperature sensors, ice detector systems. |
| Science Associates<br>PO Box 230<br>Princeton NJ 08542<br>(609) 924-4470 | General meteorological equipment |
| Science Engineering Associates<br>PO Box 115<br>South Willington CT 06265<br>(203) 487-1869 | Aircraft data systems |
| University of North Dakota<br>Center for Aerospace Studies<br>PO Box 8216 University Station<br>Grand Forks ND 58201<br>(701) 777-2791 | Aircraft cloud physics services, meteorological data analysis |
| University of Wyoming<br>Dept. of Atmospheric Science<br>PO Box 3038 University Station<br>Laramie WY 82071<br>(307) 766-4947 | Aircraft cloud physics services, meteorological data analysis. |
| Vaisala, Inc.<br>2 Tower Office Park<br>Woburn MA 01801<br>(617) 933-4500 | Upper air sounding systems, laser ceilometers, temperature/humidity sensors, general meteorological equipment |
| WeatherMeasure<br>1165 National Drive<br>Sacramento CA 95834<br>(916) 928-1000 | General meteorological equipment |
| Weather Modification Inc.<br>PO Box 198<br>Bowman ND 58623<br>(701) 523-5606 | Aircraft data systems, aircraft contract services |

★ U.S. GPO:1991 573-185/20,018

## Mission of the Bureau of Reclamation

*The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.*

*The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.*

*Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.*

A free pamphlet is available from the Bureau entitled "Publications for Sale." It describes some of the technical publications currently available, their cost, and how to order them. The pamphlet can be obtained upon request from the Bureau of Reclamation, Attn D-7923A, PO Box 25007, Denver Federal Center, Denver CO 80225-0007.