R-89-02

WINTER CLOUD SEEDING POTENTIAL ON THE MOGOLLON RIM

FINAL REPORT

PREPARED FOR

ARIZONA DEPARTMENT OF WATER RESOURCES

UNDER IGA-88-6189-000-0051

JANUARY 1989

U.S. DEPARTMENT OF THE INTERIOR
Bureau of Reclamation
Denver Office
Research and Laboratory Services Division
Water Augmentation Group

7-2090 (4-81)
Bureau of Reclamation

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.
R-89-02

2. GOVERNMENT ACCESSION NO.

3. RECIPIENT'S CATALOG NO.

4. TITLE AND SUBTITLE
WINTER CLOUD SEEDING POTENTIAL ON THE MOGOLLON RIM - FINAL REPORT PREPARED FOR ARIZONA DEPARTMENT OF WATER RESOURCES UNDER IGA-88-6189-000-0051

5. REPORT DATE
January 1989

6. PERFORMING ORGANIZATION CODE
D-3720

7. AUTHOR(S)
Arlin B. Super, Edmond W. Holroyd, III, and Jack T. McPartland

8. PERFORMING ORGANIZATION REPORT NO.
R-89-02

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Bureau of Reclamation
Denver Office
Denver CO 80225

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.
IGA-88-6189-000-0051

12. SPONSORING AGENCY NAME AND ADDRESS
State of Arizona
Department of Water Resources
15 South 15th Avenue
Phoenix AZ 85004

13. TYPE OF REPORT AND PERIOD COVERED

14. SPONSORING AGENCY CODE
DIBR

15. SUPPLEMENTARY NOTES

Microfiche and hard copy available at the Denver Office, Denver, Colorado.

16. ABSTRACT

Natural cloud and precipitation processes were investigated on the Mogollon Rim of Arizona during mid-January to mid-March of 1987 and 1988. The primary goal was to evaluate the cloud seeding potential of winter storms prior to attempting any seeding. It was crucial to monitor the availability of supercooled CLW (cloud liquid water) required for precipitation development, and this was accomplished with a ground-based microwave radiometer and instrumented aircraft. Other measurements of importance included cloud depth and structure, atmospheric stability, winds, cloud ice particles and water droplets, and surface precipitation. The field measurements were put in the context of large-scale weather patterns using standard weather maps and satellite photographs. A secondary goal involved evaluation of ground-based seeding simulated by transport and diffusion experiments using a tracer gas. Several important findings emerged from the various analyses of the data. Cloud liquid water was available during portions of most storm episodes. The flux of liquid water passing over the crestline during a 4-month winter was estimated at 30 to 100 percent of the mean annual runoff from the study areas. Thus, the raw material required for successful cloud seeding was available in reasonable abundance. The majority of the total CLW flux for each season was produced during a few large storms that were efficient in producing snowfall during portions of their lifetimes but quite inefficient during other periods. The total flux for both seasons was approximately equally divided between 326 hours (85 percent of all hours) with vertically integrated CLW amounts less than 0.20 mm and 59 hours (15 percent) with amounts between 0.20 and 0.65 mm. The amount of CLW produced by local storms or isolated clouds was limited. The transport and diffusion studies revealed that plumes of ground-based seeding material could usually fill most of the lowest kilometer of cloudy air passing over the crest during periods with stratiform clouds. However, this zone was often too warm for significant ice nucleation with conventional types of silver iodide and generators. Aircraft seeding would likely be required for a large fraction of the Arizona storm clouds. Recommendations are made for future experiments designed to document the physical chain of events following particular seeding treatments.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS-- Weather modification/ cloud seeding/ precipitation augmentation/ precipitation enhancement/ artificial seeding/ cloud physics/ orographic clouds/ supercooled liquid water/ cloud liquid water/ liquid water content/ ice crystals/ snow/ precipitation/ plume tracking/ transport and diffusion/ clouds/

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

c. COSATI Field/Group 04B   COWRR: 0402.1   SRIM:

18. DISTRIBUTION STATEMENT
Available from the National Technical Information Service, Operations Division, 5285 Port Royal Road, Springfield, Virginia 22161.

19. SECURITY CLASS (THIS REPORT)
UNCLASSIFIED

20. SECURITY CLASS (THIS PAGE)
UNCLASSIFIED

21. NO. OF PAGES
173

22. PRICE

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SI METRIC

January 1989

UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

ACKNOWLEDGMENTS

The investigations discussed in this report were jointly supported by the Arizona Department of Water Resources; Bureau of Reclamation, Lower Colorado Region; Central Arizona Project Association; Central Arizona Water Conservation District; Maricopa Water District; and Salt River Project.

Several other agencies provided substantial assistance in conduct of the project. Significant contributions were made by the Federal Aviation Administration: Albuquerque Air Route Traffic Control Center, Scottsdale Flight Standards District Office, and Prescott Flight Service Station; U.S. Forest Service; Apache, Coconino, Prescott, and Sitgreaves National Forests; and U.S. Department of the Interior, Office of Aircraft Services.

Don Griffith, John Thompson, Bill Hauze, Rich Benner, George Wilkerson, and Marty Thorp of North American Weather Consultants made substantial contributions to the 1987 field program.

Wayne Sand and George Bershinski of the University of Wyoming capably managed the research aircraft program and provided their skills as pilots.

John Lease provided direction for the Bureau of Reclamation's Water Augmentation Group. Others from this group who made significant contributions include Mike Collins and Glenn Cascino who provided electronics expertise and, in particular, Bruce Boe who accomplished substantial software development and preliminary analysis in support of this work, including section 5.8.

Mary Ann Trujillo made significant editing and organizational contributions to the final report.

EXECUTIVE SUMMARY

This report documents the data collection and subsequent analyses from the first two field programs of the Arizona Snowpack Augmentation Program. The purpose of these field programs was to examine the suitability of winter clouds over the Mogollon Rim area for possible future weather modification activities aimed at increasing water supplies. Only naturally occurring cloud systems were studied during the period of this report, and no cloud seeding was conducted.

Measurement programs were carried out during the mid-January to mid-March period of both 1987 and 1988. Two different primary ground-observing sites were used, both near the crest of the high terrain. During early 1987, that site was Happy Jack, south of Flagstaff, while Hannagan Meadow in the White Mountains of eastern Arizona was used in early 1988. The 1987 program was more comprehensive, including aircraft, radar, and other observations not available during 1988.

One of the initial analysis efforts was to develop a storm episode classification system. In its final form, each hour of each storm was typed by the scale of the weather disturbance causing it, whether synoptic (affecting a large area) or mesoscale (affecting a local area), and by the presence or absence of significant convection; that is, whether the clouds were predominantly stratiform or convective. This dual classification provided a framework for other analyses.

The most important field observations were of cloud liquid water, chiefly collected by a ground-based microwave radiometer. This relatively new instrument can continuously monitor the vertically integrated amount of cloud liquid water above it. Winter precipitation over the Mogollon Rim is produced when the normally supercooled (colder than 0 °C) cloud liquid water is converted into tiny ice particles that grow to snowflake size and settle to the surface. Consequently, it is very important to measure the cloud liquid water overhead as it is the "raw material" or "fuel" for precipitation.

It is known that cloud liquid water often forms over the windward side of mountain barriers due to the uplift and associated cooling of moist air. Conversely, the cloud liquid water rapidly evaporates on the lee side due to subsidence and warming of the air, resulting in the well-known "rain shadow" effect downwind of many mountain ranges. In the Arizona studies, the radiometer was located so it could monitor the cloud liquid water passing over the crest just prior to the evaporation zone. The cloud liquid water can therefore be thought of as excess to that used by nature in producing precipitation because any cloud liquid water still existing above the crest would likely soon evaporate. Similarly, small ice particles flowing over a mountain crest soon begin sublimating. Therefore, successful cloud seeding involves converting excess cloud liquid water into tiny ice crystals far enough upstream to permit growth into snowflakes that reach the surface before sublimating in the lee of the barrier.

A number of findings resulted from applying the storm classification scheme to the cloud liquid water observations. For example, the large majority of hours with cloud liquid water were produced by synoptic scale disturbances. This suggests that the larger storms have the most potential for snowfall enhancement by cloud seeding. Several of the storm episodes had apparently seedable conditions (excess cloud liquid water) during their beginning and ending portions, usually associated with shallow clouds. An abundance of cloud liquid water was sometimes found during the middle portions as well, again often with shallow clouds. But important exceptions existed when cloud liquid water coexisted with moderate to heavy snowfall rates. Such cases had strong winds that apparently produced significant uplift over the mountain barrier, resulting in production of liquid water condensate at rates in excess of natural conversion to snowfall.

Examination of cloud top observations by radar revealed that more than half of all 1987 hours with cloud liquid water were with shallow clouds extending no more than 2.5 kilometers above the Happy Jack site. But such clouds produced only 12 percent of the total precipitation during the field program. This suggests these clouds may be the best candidates for seeding.

Considerable temporal variability in cloud liquid water amount was usually seen throughout the course of each storm. Time histories indicated rapid changes from periods with abundant cloud liquid water and little or no precipitation, indicating inefficient clouds, to very efficient precipitation producing clouds. Thus entire storm episodes cannot be thought of as simply seedable or nonseedable. Rather, the seeding potential of most storms varies considerably over relatively short time periods (hours) with portions appearing seedable and other portions appearing naturally quite efficient at producing precipitation. Further, while some apparently seedable (or nonseedable) periods last for several hours, others may be very brief. These temporal observations are based on radiometer measurements above a single site. Aircraft sampling revealed pronounced spatial variations of cloud liquid water as well.

It is important that these results be incorporated into planning of future seeding strategies. It will be very difficult, and often impractical, to rapidly change the seeding treatment in response to the short-term changes in seedability observed during most storm episodes. The only practical approach may be to seed throughout entire storm episodes, assuming that seeding during naturally efficient periods results in negligible reduction in snowfall. Some winter seeding projects in the western mountains of the United States have suggested this hypothesis is valid, but it should be tested in Arizona prior to operational seeding of entire storm periods.

For the two-season data set, cloud liquid water was more commonly associated with stratiform clouds than convective clouds. However, because the difference was not great, both cloud types are important for cloud seeding potential. Most of the convection was embedded in general cloud layers and rather weak as indicated by visual observations and aircraft measurements of limited liquid water amounts. More vigorous convection was sometimes apparent, and occasionally thunder was heard.

Isolated towering cumulus clouds occurred on some days, but their contribution to the radiometer-observed cloud liquid water was limited. In-depth analysis incorporating all available surface and aircraft data suggested that isolated convective clouds offer little winter seeding potential over the Mogollon Rim.

The presence of cloud liquid water and occurrence of precipitation were quite dependent upon wind direction at both field locations. Southwesterly flow was most important at Happy Jack with northeasterly flow also significant. Westerly flow dominated the cloud liquid water and precipitation periods at Hannagan Meadow. In all these cases, the winds are generally perpendicular to the mountain barrier, thereby maximizing uplift of moist air and the resulting condensation into cloud droplets that was sometimes followed by snowfall.

Cloud liquid water was observed over 400 hours during the two field programs or, on average, about 100 hours per month. The vertically integrated mean amounts were less than 0.1 mm for over half the hours, suggesting limited cloud liquid water contents as verified by aircraft observations. Similar liquid water contents have been found during winter at a number of other mountain locations in the West; yet the times with limited liquid may be important in future operational cloud seeding because the many hours of occurrence could result in significant snowfall accumulation. Conversely, the infrequent hours with abundant cloud liquid water may also have significant weather modification potential through potentially higher snowfall rates. It is of interest that much of the seasonal snowpack in the western mountains is typically produced by many hours with light snowfall. But the presence or absence of a few big storms with high precipitation rates can result in large departures from a "normal" seasonal snowpack.

Cloud liquid water episodes varied in length from 1 to 80 hours, but the seven episodes lasting 30 hours or more accounted for half the observed hours with liquid cloud over the radiometer. The overhead flow or "flux" of cloud liquid water was estimated for each storm episode by incorporating windspeed measurements at cloud levels. It was found that only three storms produced about 75 percent of the seasonal flux in 1987, and a single storm provided approximately 67 percent of the 1988 flux. Both these findings further emphasize the importance of the major storm events in seasonal cloud liquid water production and, thereby, seeding potential. Ranges of observed cloud liquid water values were converted to probable precipitation rates for ease of comprehension. It was shown that cloud seeding could rarely produce more than a few millimeters per hour of snow water equivalent (or few centimeters per hour of snow depth) because, like natural snowfall, seeding-produced snowfall is limited by the availability of cloud liquid water flux.

The total cloud liquid water flux for the two field seasons was compared with mean annual runoff from high-elevation watersheds in the same areas. The 1987 flux was equivalent to about half the runoff while the 1988 season, which had few large storms, had a flux equivalent to 14 percent of the runoff. For a first approximation in the absence of additional data, let it be assumed that these values represent typical "wet" and "dry" winters; then 4-month winter seasons would usually have cloud liquid water fluxes ranging from about 30 to 100 percent of the mean annual runoff from the same high elevation watersheds. This is a considerable amount of excess water passing over the barrier crests and gives cause for optimism about the potential of cloud seeding. It is, of course, important to determine what fraction of the excess water can be converted to additional precipitation by seeding. But even conversion of a small fraction into additional precipitation could be quite beneficial in enhancing streamflow and ground-water supplies.

Analysis of aircraft microphysical observations obtained during early 1987 was usually supportive concerning cloud seeding potential, particularly in regard to a general absence of significant "ice multiplication." Ice multiplication has been observed in some winter clouds; for example, over the Sierra Nevada of California where large concentrations of ice particles often develop through microphysical processes. This often results in efficient natural conversion of cloud liquid water to precipitation and little or no cloud seeding potential. It is known that cloud droplets larger than about 24 micrometers in diameter need to be present in significant concentrations as one condition of an important ice multiplication process. However, the Arizona cloud droplets were rarely that large, suggesting that ice multiplication by that process should be infrequent.

Measurements of ice particle concentrations were examined from the many aircraft missions over the Mogollon Rim. The median concentration was about 1 per liter with most values between 0.1 and 10 per liter. As expected, there was a tendency for higher concentrations at colder temperatures. These relatively low values also argue against ice multiplication and indicate that the ice crystals sampled by aircraft were generally caused by primary nucleation due to ice nuclei. However, a note of caution is in order. There is reason for concern about the representativeness of the 1987 aircraft sampling. Further, ice multiplication may have sometimes occurred below aircraft sampling levels.

Aircraft observations of liquid water contents were usually limited to low values, presenting a less optimistic assessment of cloud seeding potential than the much more abundant microwave radiometer measurements. This is believed to be partially due to a demonstrated bias in the aircraft sampling periods such that the wetter storm periods were not measured. Further, it is suspected that higher amounts of liquid water often existed below permissible aircraft altitudes, but no direct measurements presently exist to test this supposition.

Most of the total precipitation at both field sites was from the synoptic stratiform storm class. The heavier snowfall episodes were created by large-scale atmospheric motions that were largely independent of the Mogollon Rim terrain. The precipitation was often initiated at high levels well upwind of the Mogollon Rim but experienced substantial growth in the locally produced cloud liquid water at low levels over the Mogollon Rim.

Precipitation rate distributions were highly skewed as is common for mountain snowfall. That is, many hours had light snowfall rates while half the total precipitation fell during only 12 percent of the hours with snowfall. Precipitation generally fell in episodes typically lasting about 1 day with longer periods of dry weather in between.

Atmospheric stabilities were examined during 1987 storms using rawinsonde and aircraft observations; in most cases, the stability was neutral. Therefore, ground-released seeding material should mix vertically, given sufficient time and distance, and not be trapped as has been the case with some mountain barriers with stable atmospheres.

A series of experiments was conducted that simulated ground-based seeding by release of a tracer gas. These experiments were highly successful in tracking the tracer gas under a variety of conditions; the results showed that seeding material, released from the surface on the windward slope of the barrier, would typically cross the crest with a plume height of over 700 meters. Plume widths were sufficient that a reasonable number of ground-based silver iodide generators could seed a large portion of the Mogollon Rim.

The observed tracer gas concentrations and prevailing temperatures during both warm and cold storms were used to estimate effective in-cloud ice nucleus concentrations for typical silver iodide generator outputs. These estimates showed that Arizona stratiform storms are usually too warm, in the layer that could be seeded from the ground, for significant ice crystal production with conventional types of generators and silver iodide. Enhanced vertical mixing to colder levels may occur during periods with embedded convection. Such conditions were not well represented in the tracer gas experiments. Further, recently developed silver iodide solutions, effective at warmer temperatures, and higher output generators should increase the fraction of storms seedable by ground release. Also, the effectiveness of various types of silver iodide requires testing in actual clouds, as the laboratory results used in the simulations may be underestimates. Therefore, while ground-based seeding of many Arizona winter clouds presently appears impractical, the economy of this approach and some uncertainties in the calculations argue for further field studies where actual seeding is conducted.

In summary, the first two field efforts for the Arizona Snowpack Augmentation Program have greatly increased knowledge of winter cloud and precipitation processes over the Mogollon Rim of Arizona. The key findings are that a considerable amount of excess cloud liquid water passes over the Mogollon Rim without being converted into precipitation. While pronounced variability existed in time and space during storm episodes, several periods were identified that were naturally inefficient in precipitation production but appeared seedable. Ground-based seeding should be feasible for the colder storms but does not initially appear practical for the warmer storm periods because the cloud layers that would be reached by the silver iodide plumes would not be cold enough for significant ice crystal formation. However, further ground-seeding studies are recommended with convective clouds and recently developed types of silver iodide. Aircraft seeding should be able to cause ice nucleation of some of the excess cloud water in both cold and warm storms at such locations that additional precipitation should reach the higher elevations of the Mogollon Rim.

It is now known that a reasonable frequency of seedable winter clouds exists over the Mogollon Rim of Arizona with significant amounts of unused liquid water. The challenge of future work will be to quantify the amount of precipitation and streamflow enhancement that cloud seeding can produce while being socially beneficial and acceptable.

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TABLES

FIGURES

FIGURES - Continued

GLOSSARY

AgI	silver iodide
$AgI-NH_4I$	silver iodide complexed with ammonium iodide
a.g.l.	above ground level
Arizona DWR	Arizona Department of Water Resources
ASAP	Arizona Snowpack Augmentation Program
CLW	cloud liquid water
CSIRO	Australian Commonwealth Scientific and Industrial Research Organization
FAA	Federal Aviation Administration
FSSP	forward scattering spectrometer probe
IFR	instrument flight rules
IPC	ice particle concentration
J-W	Johnson-Williams
mb	millibar
MC	mesoscale convective
MS	mesoscale stratiform
m.s.l.	mean sea level
m.s.t.	mountain standard time
NAWC	North American Weather Consultants
NE	nonepisode
NH_4ClO_4	ammonium perchlorate
NWS	National Weather Service
Pibal	pilot balloon
ppt	parts per trillion
PROBE	Portable Remote Observations of the Environment
Reclamation	U.S. Department of the Interior, Bureau of Reclamation
SC	synoptic convective
SCPP	Sierra Cooperative Pilot Project
SF_6	sulfur hexafluoride
SLIP	supercooled liquid production
SLW	supercooled liquid water
SS	synoptic stratiform
TD	threshold diameter
USFS	U.S. Forest Service
VFR	visual flight rules
1D-C	one-dimensional cloud particle imaging probe
2D-C	two-dimensional cloud particle imaging probe
2D-P	two-dimensional precipitation particle imaging probe

1. INTRODUCTION

1.1 General

This report discusses the collection and analyses of meteorological data obtained by the Bureau of Reclamation during the first two exploratory observational programs for the ASAP (Arizona Snowpack Augmentation Program). Field observations were made in the Mogollon Rim area of Arizona during the periods of January 14 through March 17, 1987, and January 15 through March 10, 1988. The work was conducted as part of a cooperative effort with the Arizona DWR (Department of Water Resources). The primary objective was to examine the water supply augmentation potential of winter storms for possible future application of weather modification (cloud seeding) technology. This was accomplished by investigating natural storms and precipitation processes. No cloud seeding was conducted during either the 1987 or 1988 studies.

1.2 Background

The Arizona DWR has a statutory requirement to include water augmentation alternatives in water management planning. One potential alternative considered by DWR is the possibility of applying cloud seeding technology to enhance winter precipitation on the higher elevations of the Mogollon Rim. Although not currently quantifiable in Arizona, increased winter snowfalls are expected to translate into additional water available to augment both instream flows and aquifer recharge.

The DWR initiated discussions with Reclamation's Water Augmentation Group (previously the Division of Atmospheric Resources Research), which directs Project Skywater--a Federal program that conducts applied cloud seeding research and development studies and assists in technology transfers to interested users. The initial discussions culminated with the finalization of an Intergovernmental Agreement between the State of Arizona and the Bureau of Reclamation. This agreement provided funds to Reclamation to conduct a feasibility study using historical climatological data. The final report for this work (Reclamation, 1987a) identified major precipitation storm-producing patterns; considered these patterns for wet, normal, and dry years; and made estimates of their augmentation potential using model studies and results from past winter programs. It was concluded that moderate potential for snowfall augmentation probably exists, at least for some storm situations.

While the climatological study was being conducted, DWR was encouraged by a broad-based group of Arizona water entities to actively pursue initiation of a long-range cloud seeding demonstration program. Reclamation was asked to assist DWR in developing alternatives. It was mutually concluded that further assessment of the augmentation potential of Arizona winter storms, based on *in situ* field measurements, should be performed prior to initiating a long-term effort. In early 1987, Reclamation and DWR reached an arrangement to conduct an initial 2-month intensive observational program over the Mogollon Rim.

Reclamation funded and conducted the initial field observation effort; DWR and other in-state cooperators provided monetary support to Reclamation for analysis of the collected data. Further negotiation in early 1988 led to a more limited observational program over a different portion of the Mogollon Rim. Funding for this 8-week effort primarily came from Reclamation while DWR and in-state cooperators again funded most of the analysis and also the preparation of this report.

1.3 Program Objectives

The general objective of the field investigations was to obtain a sufficiently comprehensive data set from which the augmentation potential of observed storms could be estimated. The primary goals for both field efforts were to:

a. Document the storm situations in which excess supercooled liquid water exists in the form of tiny cloud droplets. - The presence of supercooled liquid water is a requirement for significant ice-phase seeding potential. Primary data used to establish the frequency of occurrence, magnitudes, and durations of supercooled liquid water events were collected using Reclamation's microwave radiometer. During the 1987 effort, these observations were supplemented by aircraft measurements, which provided information on the spatial distribution of supercooled liquid water.

b. Establish the meteorological conditions necessary for supercooled liquid water production and depletion. - Local and synoptic scale data were collected to classify storm types and identify specific storm phases that produce supercooled liquid water in excess to that used in the natural precipitation process.

c. Obtain the wind measurements necessary to estimate the amount of supercooled liquid water transported over the target drainage areas. - This provides the upper limit for cloud seeding potential as precipitation is derived from supercooled liquid water.

d. Estimate the potential for seeding with ground-released ice nucleation agents through tracer transport and diffusion studies. - Downwind measurements of the ground-released tracer gas were made with an instrumented aircraft.

1.4 Report Contents

This report describes the field efforts, subsequent data analyses, and conclusions reached using combined data from the two field programs. An executive summary is provided at the beginning of the report. Field site selection, program organization and scheduling, and observed weather in relation to historical normals are discussed in section 2. Field instrumentation and its use are described in section 3. (Those readers not interested in field operations and equipment details may wish to resume reading at section 4.)

Analyses and results are first discussed in section 4 where observed storms for each season are classified in relation to prevailing synoptic weather patterns and are further subdivided into specific storm phases that produce supercooled liquid water. The ground measurements concerning supercooled liquid water availability are treated in detail and the seasonal augmentation potential is estimated in section 5. Microphysical and snowfall characteristics of the storms are analyzed in section 6, and detailed case studies are presented in section 7 for storms of particular interest. Section 8 addresses the seeding potential for isolated convective cells, which were observed in 1987. The 1987 experiments simulating ground-based seeding are presented in section 9, and implications for possible future operational seeding efforts are discussed. Finally, section 10 provides a concise summary of the major conclusions reached concerning the augmentation potential for Arizona winter storms and makes recommendations for future work. The appendix contains details concerning each storm's evolution while passing over the respective project areas in early 1987 and early 1988.

2. FIELD PROGRAMS: SITE SELECTION, SCHEDULING, AND GENERAL WEATHER

2.1 Research Areas and Site Selection

2.1.1 The Early 1987 Field Program. - An initial conceptual program plan was formulated by Reclamation in July 1986. At that time, preliminary findings from the ongoing feasibility study were reviewed, key areas of uncertainty established, and a range of budget-dependent program options developed. It was immediately agreed that a program integrating both ground and aircraft observing systems would provide the most effective approach for estimating winter storm augmentation potentials. Ground instrument systems were available that could provide essentially continuous measurements of certain key parameters. These instruments could be supplemented by an adequately equipped research aircraft to provide more detailed measurements on an intermittent basis. A detailed description of the various instrumentation systems is found in section 3.

Critical items, which would necessitate long lead times to procure or negotiate, were identified and efforts started in these areas. Primary among these items were selecting field sites, obtaining services of an adequate research aircraft, and establishing working arrangements with the necessary FAA (Federal Aviation Administration) groups. Initial efforts were focused on development of site selection criteria for both the general study area and specific function sites. The criteria and constraints established were as follows:

a. The study area had to be located so that additional water produced through future cloud seeding would primarily augment either the Verde or Salt Rivers or both.

b. A significant amount of terrain above about 2 km elevation had to lie within the study area to induce orographic uplift to intensify storm clouds and provide seasonal snowpack storage (although Arizona snowpacks often partially melt during warm periods between storms).

c. The airspace over the study area had to be sufficiently free of conflicts so that research aircraft could be operated without undue FAA air traffic control restrictions.

d. A suitable ground-observing site had to be available in the study area near the crestline of the Mogollon Rim. This site had to have commercial electrical power, adequate-sized forest clearings for proper equipment siting, good all-weather road access, telephone service, and convenient location for crew accommodations.

e. An airport infrequently closed to flight operations during storm periods had to be available within about 20 minutes flight time from the study area. Minimum requirements for this facility included: a published instrument approach procedure; sufficient runway length to accommodate the research aircraft contemplated; fuel and hangar availability; and existence of nearby office and personnel accommodations.

f. A suitable upwind (generally southwest) site for taking upper air soundings had to exist within approximately 40 km of the highest elevation portion of the study area. This site had to have commercial power, telephone service, and nearby crew accommodations.

g. Small, sheltered forest clearings had to be available within the study area for location of precipitation gauges. These needed to be close to all-weather roads for convenient winter access and be easily obtainable for short-term use through lease or other arrangements.

After reviewing topographic map information, three areas of the Mogollon Rim (see fig. 2-1) were identified as potential candidates for conduct of the program: (a) an area from Flagstaff extending south-southeast approximately 80 km, (b) the Mogollon Rim area from northwest through northeast above Payson, and (c) the White Mountains area in eastern Arizona. The latter was eliminated from consideration for the initial field work when preliminary discussions with the FAA disclosed severe airspace utilization conflicts. Much of the area of interest was occupied by restricted military operational areas, which often precluded civilian aircraft use. Although the potential exists to negotiate alternate military operational area boundaries for a future long-term program, it was clearly not possible to implement any changes within the time available.

In late July 1986, an initial area familiarization visit was made by Reclamation personnel to intensively review the two remaining candidate sites. Following this visit, additional data and clarifications were obtained from several sources. Consideration of all factors led to the preliminary selection of the area south-southeast of Flagstaff as the most suitable for intensive studies involving combined ground instrumentation and aircraft operations. The principal reasons for this decision were as follows:

a. Airspace utilization limitations were the least restrictive. A formal request was submitted to the FAA Albuquerque Air Route Traffic Control Center to establish a Letter of Agreement that would define research airspace utilization areas and coordination procedures. The three specific operation areas requested are shown as areas 1, 2, and 3 in figure 2-2. The initial FAA response indicated that, while the request could be accommodated in general terms, restrictions could often be expected in area 3 as it had a major arrival/departure corridor for many Phoenix area commercial flights. It was suggested that area 2 would offer the most operational flexibility. Area 1 was considered too small to be a primary site.

b. A suitable site existed for installation of the primary collection of ground instrumentation. This was near the USFS (U.S. Forest Service) Long Valley District Ranger Station at Happy Jack, Arizona (see fig. 2-2). The land was under the jurisdiction of the Coconino National Forest, and preliminary discussions with USFS personnel indicated a likelihood that both land use arrangements and provision of other services could be negotiated. Commercial power and telephone service were both available as were unused concrete pads from some former buildings, which were ideal for siting some of the equipment. The Happy Jack site appeared to best meet the selection criteria.

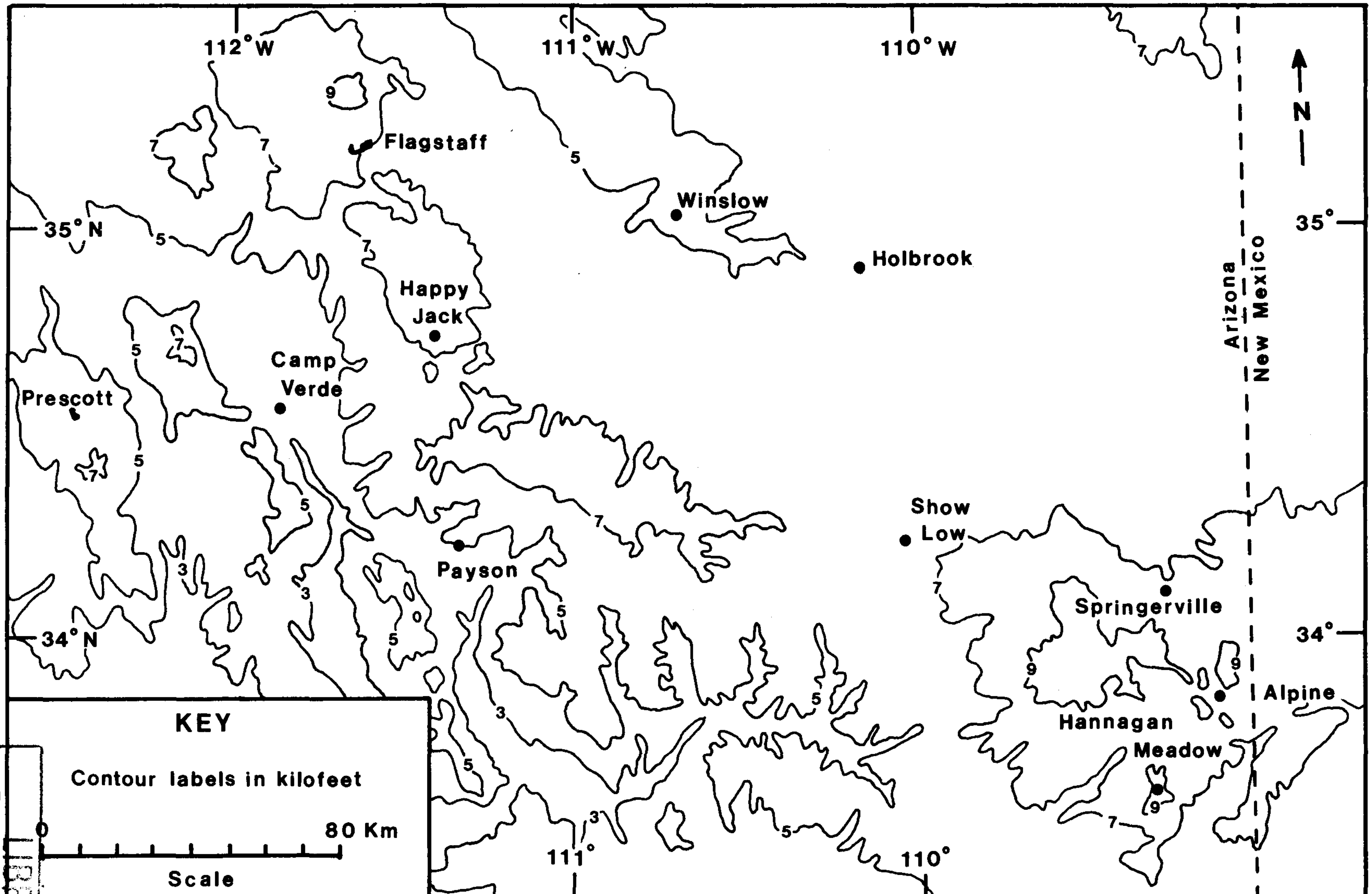


Figure 2-1. - Map of Mogollon Rim portion of Arizona showing locations of major ground instrumentation (Happy Jack in 1987 and Hannagan Meadow in 1988) and nearby towns.

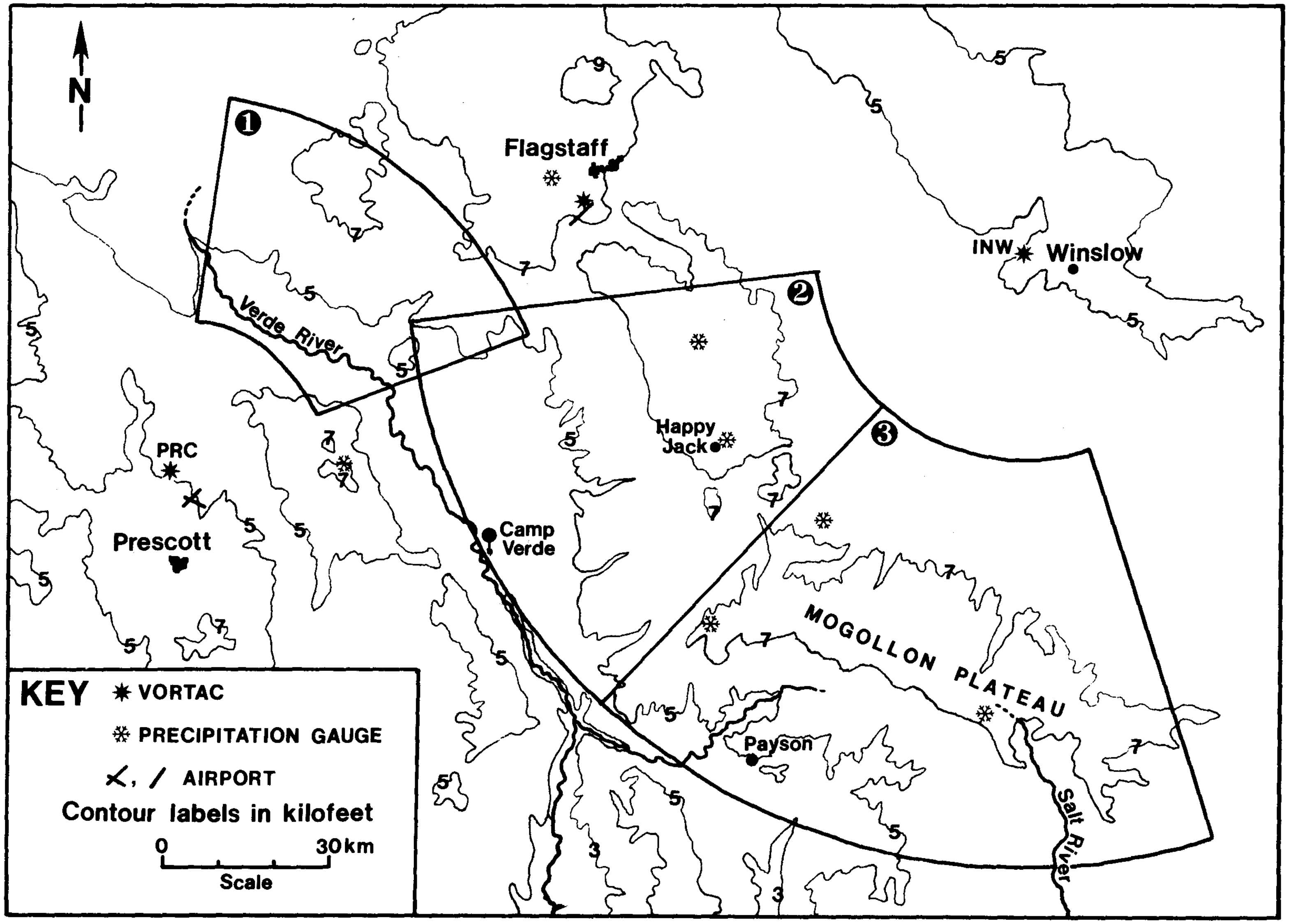


Figure 2-2. - Map of 1987 project area in Arizona. Aircraft operations were concentrated in area 2, especially near Happy Jack.

c. The general terrain within area 2 was considered more suitable for the investigations than that in the other areas. Area 2 has a well-forested, gently sloping, high altitude catchment area that drains into the Verde and Little Colorado Rivers. Additional areas of high ground bordered the area from the southwest to west and made ideal release points for tracer materials to simulate seeding from a ground generator network.

Major operating sites under consideration were subjected to a field review during late August 1986, and arrangements for their use were largely completed in September and October. The principal decisions and steps taken in this process were as follows:

a. A reinspection of the Happy Jack site confirmed that it was the best location for an extensively instrumented ground facility. Potentially suitable locations were found at the site for all anticipated instrument observing systems although two unresolved problem areas remained; these were (1) a question regarding the adequacy of the largest clearing size for operation of a doppler acoustic sounder wind-measuring system, and (2) a concern that use of a C-band radar system might interfere with USFS communications equipment. Field equipment tests were arranged and conducted with no problems ultimately disclosed in operating the radar system. The wind system proved to provide intermittent data during some conditions, especially in the lower levels and with strong winds. However, the site was judged adequate.

b. A suitable upwind upper air sounding (rawinsonde) site was identified near the town of Camp Verde. An instrument and supply storage facility and locations for equipment and personnel trailers were determined. Arrangements were also made for installation of telephone service.

c. The airport at Prescott was identified as both the research aircraft and project headquarters base. The field was the only one outside the Phoenix area that met the established airport selection criteria minimums. The facility had an instrument landing system precision approach; temporary hangar space was tentatively identified as being available, runway lengths were adequate, and weather closures were historically infrequent. Suitable office space for the project headquarters was located, and availability was confirmed of weather forecast products at the FAA Flight Service Station.

d. The Payson airport was selected as a location for installation of a 16-mm time-lapse movie camera to monitor cloud conditions over the Mogollon Rim to the north.

Two Interagency Agreements were negotiated with the USFS. The first, with the Coconino National Forest, provided for use of the Happy Jack site. The second agreement was reached with the Prescott National Forest. This provided office, storage, and aircraft ramp parking space at the Prescott airport at a facility used as an air tanker base during the summer fire season.

A procurement package was prepared to obtain the services of an existing fully functional research aircraft. The contracting was done through the Department of the Interior Office of Aircraft Services. The aircraft solicitation was completed and issued for bids to qualified respondents in mid-October 1986. This effort culminated with a signed contract with the University of Wyoming in early December. The contract provided the following: (a) aircraft and pilot for a 60-day period; (b) up to 90 hours of research flight time; (c) a computer subroutine that would allow the aircraft data tapes to be processed with Reclamation's computer system; and (d) installation of a leased SF_6 (sulfur hexafluoride) detector system for transport and dispersion studies.

Interactions with the FAA were continued to finalize airspace arrangements. Two separate but interrelated documents were finally consummated. The first was a Certificate of Authorization obtained from the Scottsdale Flight Standards District Office. This instrument allowed the research aircraft to legally deviate from regulations concerning minimum permissible altitudes above ground during instrument flight in mountainous areas [FAR 91.119 (a)(2)(i)]. Normally, a 610-m minimum clearance is required; but the authorization allowed operations within 305 m of the highest terrain. The second document, conditional upon approval of the first, was a Letter of Agreement established with the Albuquerque Air Route Traffic Control Center. The letter formally defined the operating areas, established responsibilities, and promulgated procedures for coordinating with the Center to utilize the airspace. This document was finalized on January 21, 1987, just prior to the scheduled start of aircraft operations.

An existing Reclamation contract with NAWC (North American Weather Consultants) was amended to allow NAWC to provide field support services in Arizona.

General locations for a network of precipitation gauge sites were first established on topographic maps. Field inspections were then carried out and specific sites selected as shown in figure 2-2.

While these efforts were taking place, the program plans were reviewed, revised, and finalized. The project operations plan was completed in mid-December and published prior to the program start.

2.1.2 The Early 1988 Field Program. - Prior to completion of the analysis of the early 1987 data set, DWR planners decided that primary emphasis should be shifted to investigating the potential of seeding to augment water supplies in the Salt River. Available funding dictated a less ambitious program than that conducted the previous winter. It was not financially possible to obtain aircraft measurements or local rawinsonde data so the primary concern was to obtain an adequate site for ground-based instruments. The characteristics sought were:

a. A high-elevation location near the drainage divide of the Salt River.

b. Reasonable road access during winter conditions, sufficiently large forest clearings to site the instruments, available commercial power and telephone service, and convenient commuting distance from a town.

Attention initially focused on the Mount Baldy area of the White Mountains. However, winter access is limited to only a few roads in the White Mountains. Some potential areas were identified, and a site selection trip was conducted in early December 1987. At that time, it was concluded that the only viable site available was at Hannagan Meadow, which is approximately 37 km south of Alpine, Arizona, on Highway 666 (see fig. 2-1). A USFS site, used as a fire crew headquarters during the summer months, was available and met the basic criteria.

An Interagency Agreement was negotiated with the USFS to allow use of the Hannagan site, and arrangements were made for modifications to the existing electrical power distribution system to accommodate the intended equipment.

Program plans and an operations schedule were completed in December 1987.

2.2 Field Scheduling and Organization

2.2.1 The Early 1987 Field Program. - Scheduling was set so that operations could be conducted on any day during the period except February 16, 1987, which was a Federal holiday. There were no other fixed days off. Instead, two 24-hour off-duty periods (not necessarily contiguous) were guaranteed within any 14 consecutive calendar days for all personnel. Offday determinations were made by the Reclamation site coordinator using all available forecast data in an attempt to select nonstorm periods. This was generally successful; no major storms were missed although isolated convective events did occur on some of the offdays.

Each afternoon or early evening, the Reclamation site coordinator and the NAWC supervisor held an outlook planning conference to plan potential activities for the following day. During this meeting, the following were reviewed:

a. The weather outlook from all available information.
b. Status and availability of all equipment and personnel.
c. Potential tasks that could be accomplished given all constraints imposed by a and b above.

Based on these discussions, the Reclamation site coordinator made a decision to follow one of three general courses of action for the following morning. The options were:

a. Declaration of an offday for all personnel (this required a high probability that no weather suitable for investigation would occur the following day).

b. A call for early operations (this was predicated on a confident expectation that storm conditions would develop after midnight and be suitable for investigation prior to sunrise).

c. A call for normal operations (this course of action was followed in all instances where a clearcut decision could not be made; as expected, this was the most frequent situation).

The decision made then was communicated to all sites.

Unless time off or early operations were scheduled, the NAWC supervisor visited the FAA Flight Service Station early the following morning to analyze the latest available weather information. A morning update meeting was then held with all Prescott personnel at about 0800 mountain standard time[1]. During this meeting, the following were accomplished:

a. Current and forecast area weather for the day were reviewed (this included reports from the other sites).

b. An equipment status report was prepared for all systems, and calibration and service requirements were reviewed.

Based on this information, the Reclamation site coordinator formulated an initial plan for the day and disseminated it to all personnel. The basic planning options were as follows:

a. Immediate establishment of an aircraft, personnel, and ground equipment operation schedule to conduct an intensive mission involving aircraft measurements.

b. Entry into a standby status while awaiting development of suitable conditions to conduct an aircraft mission. In these instances, personnel were informed as to the type of actions which might be required later in the day; and a definite time schedule was established for later updates. A "nowcasting" mode was immediately entered and routine monitoring of all weather information sources initiated, particularly the conditions observed at the Happy Jack site. If suitable conditions occurred, all required personnel were notified and the scheduled operation started. Failing the start of a mission by late afternoon, the Reclamation site coordinator and NAWC supervisor met once again to further review conditions and make a decision whether to continue the standby status or terminate for the day.

c. Immediate stand-down for any flight operations and entry into routine daily ground operations, maintenance and calibration of equipment, data reduction, and data analysis.

2.2.2 The Early 1988 Field Program. - Initially, scheduling was set so that two Reclamation scientists were available to operate all equipment at Hannagan Meadow 24 hours per day for the entire field season except for January 18, which was a Federal holiday. The two persons alternated 24-hour shifts at the site, with crew changes at noon each day. Crew quarters for the onsite person consisted of a small camper trailer. Motel accommodations in Alpine, Arizona, were used for the off-duty person. Telephone and backup radio communications were provided between these two facilities and a routine schedule established for mandatory communications to ensure the continuing safety of the onsite person. Failure to establish communications would have been cause for the Alpine-based person to initiate a series of fixed procedures to quickly check on the Hannagan Meadow person; this was never necessary.

Reclamation staffing reductions announced in late January necessitated changes in site staffing. It was desirable to accelerate work on computer data reduction and analysis programs at Reclamation's Montrose, Colorado office so these tasks could be completed sooner than originally planned. Accordingly, after

[1]All time reported is mountain standard time.

February 11, 1988, the field site was operated by one person. Separate individuals rotated approximately every 2 weeks. Safety compromises were alleviated by making arrangements with the owners of the Hannagan Meadow Lodge to perform routine crew checks. This was facilitated by installation of a portable radio system at the lodge.

The on-duty person utilized all available weather information to schedule off-time periods.

2.3 Observed Weather in Relation to Historical Normals

2.3.1 The Early 1987 Field Season. - The representativeness of the Happy Jack area weather during the early 1987 observational period can be addressed by reference to the 30-year (1951 to 1980) averages (normals) for the Flagstaff airport, based on NWS (National Weather Service) observations. The airport is located only 50 km north of Happy Jack and is at almost the same altitude. Its normal number of days with measurable precipitation (equal to or greater than 0.25 mm melted water equivalent) for January, February, and March were 7.5, 6.5, and 8.4, respectively. During 1987, the corresponding numbers were 10, 14, and 10; the period had more frequent storms than typical, especially during February. Normal monthly precipitation at Flagstaff was 53, 50, and 54 mm for the same months; 1987 totals were 64, 65, and 43 mm. These are 121, 130, and 80 percent of normal, respectively. The major storm of February 23-26 contributed 45 mm to the monthly total, and significantly larger amounts were measured to the south and west of Flagstaff. Since maximum and minimum monthly precipitation totals ranged widely during the 30-year period for which normals were calculated (from 0 to 198 mm), the 1987 amounts can be considered reasonably near normal.

Monthly mean temperature was 0.3 °C less than normal in January, 0.2 °C greater than normal in February, and 0.9 °C less than normal in March. The mean sky cover was 5.3 tenths in January 1987, right at normal; 6.3 tenths in February 1987, above the normal of 5.1; and 5.5 tenths in March, near the normal of 5.2.

Overall, the early 1987 weather at Flagstaff appears to have been near normal except that February was somewhat cloudier and had more frequent precipitation events, but little more total precipitation than normal in spite of one major storm event. For a first approximation, the 1987 winter observational period can be considered rather typical of Arizona winters although clouds and precipitation were somewhat more frequent than normal.

2.3.2 The Early 1988 Field Season. - It is difficult to determine how typical the weather was during the early 1988 field program at Hannagan Meadow. The White Mountains are isolated and far from any NWS office. The region has a low population density with few cooperative weather observers. Consequently, there are limited long-term records to compare with 1988. The nearest reliable high elevation station is operated by the USFS in Alpine, about 37 km northeast of Hannagan Meadow and about 300 m lower. Only daily precipitation and temperature observations are collected there.

During January 1988, Alpine received 20 mm of precipitation, 17 mm below normal. February precipitation was 36 mm, 9 mm above normal. The March amount was only 0.5 mm, way below the normal of 29 mm. The monthly climatological data summaries for Arizona show graphs of monthly precipitation departures by divisions within the state. Hannagan Meadow is at the north edge of the southeast division, which had essentially normal precipitation during January, slightly below normal during February, and far below normal during March. The normal number of days with measurable precipitation are not listed for Alpine; however, the days for January, February, and March 1988 were 4, 10, and 1, respectively; those for January and March appear quite low for a station at over 2.45 km elevation.

Temperature departures are not listed for Alpine. Those stations that are listed in the southeast division averaged slightly colder than normal during January, 1.7 °C greater than normal during February, and 0.7 °C greater than normal during March.

Overall, the impression is that the Hannagan Meadow region experienced warmer than normal temperatures and below normal snowfall amounts due to a limited number of storm passages during the early 1988 observational period. The discussion in section 5 concerning 1988 cloud liquid water observations will show the storm passages were much less frequent than in 1987, in general agreement with the climatological information.

3. FIELD INSTRUMENTATION AND UTILIZATION

3.1 Early 1987 Field Instrumentation

An extensive collection of equipment was installed and operated to provide the data necessary for meeting the program objectives stated in section 1. The specific instrument systems located at each of the primary ground sites, their function, and the personnel and auxiliary facilities used to conduct the operations are summarized below.

3.1.1 Happy Jack Site. - The primary complement of ground instruments was installed and operated at the Happy Jack site (see fig. 2-1). The site is close to the drainage divide between the Verde and Little Colorado Rivers and provided an excellent location from which to estimate the amount of cloud liquid water flux passing out of the Verde drainage. The equipment, facilities, and personnel used were as follows:

a. C-Band Radar. - Reclamation's SWR-86 C-band (5.4-cm wavelength) radar system was used in a range height indicator mode to monitor cloud base and top altitudes, and reflectivity values at 5-minute intervals during storm episodes. The primary function of these data was to establish the cloud types passing overhead. Systems with relatively flat tops and generally uniform reflectivity values imply stable orographic situations; irregular tops with cellular areas of higher reflectivity indicate more unstable conditions with embedded or isolated convection. Additionally, the data could be used to estimate the relative precipitation intensities and, in conjunction with measurements from other sensors, to estimate cloud top temperature variations.

The radar unit was in a self-contained van. The unit was microprocessor-controlled and wrote digital data to 9-track magnetic tape. Peak transmitted power was 250 kW, beam width was 1 degree using a 4.27-m-diameter reflector, and data were recorded in 125-m range bin intervals. Operator displays were available for monitoring real time observations. The unit was installed, calibrated, and fully functional for the first day of the field season. It was operated in a data recording mode any time storm conditions were either anticipated or actually occurring. During fair weather conditions, the transmitter was left in a standby mode and recording discontinued. Reliability was good except for the period from the early morning of February 4 until the evening of February 13, 1987, when the unit was out of service due to failure of a major component (the pulse forming network in the transmitter section) for which there was no spare in inventory.

The system was electronically calibrated on an approximate weekly schedule by a Reclamation electronics technician. No significant shifts occurred during the season. The standard calibration checked the receiver sensitivity, digital video integrator processor level settings, pulse repetition frequency, and transmitter power. The net system gain was field checked by the suspended calibrated sphere method on March 3, 1987, using two different sphere sizes. The gain values determined from this test were consistent with previous values. Calibration and data tapes were routinely forwarded to the Montrose office for computer processing and quality control checks.

b. Microwave Radiometer. - Reclamation's microwave radiometer system was installed and operated at a location directly adjacent to the C-band radar. This relatively new instrument provides the ability to measure and record the amounts of both water vapor and liquid water integrated along the instrument's field of view (about 2.5 deg). These measurements are accomplished passively by monitoring incoming natural radiation at frequencies of 20.6 GHz (1.45 cm) and 31.6 GHz (0.95 cm). The magnitude of the signals received can be related to the total vapor and liquid present, but no ranging information is available. The general location of any liquid observed can be inferred from other data sources such as the radar derived cloud top. The unit was operated in a vertically pointing mode to provide a measure of the amounts of liquid water and vapor directly overhead. Since the Happy Jack site was near the drainage separating the Verde and Little Colorado Rivers, the unit provided the basic data to estimate the amount of liquid water not transformed into precipitation or very small ice crystals prior to entering the Little Colorado drainage during all storms with a westerly flow component. Downslope motion and cloud evaporation would be expected downwind (east) of Happy Jack.

The radiometer is located in a self-contained van, which is equipped with a parabolic reflector assembly to focus the incoming radiation on the radiometer sensor. This reflector was coated with a hydrophobic paint to minimize wetting during rain or wet snow occurrences and equipped with a fan to prevent dry snow from accumulating. The onsite technicians routinely checked the reflector, removed any snow accumulations, and dried the reflector if necessary. The van contained the sensor electronics, an LSI-11 computer for operating the system and processing the raw signals, as well as disk drives and a tape drive for recording the data in time-referenced format. The data were routinely shipped to Montrose for quality assurance checks and processing.

The radiometer was highly reliable. Data were recorded continuously throughout the program with no loss due to system failures. Small gaps in the records were produced each 6 hours when the unit automatically performed internal self calibrations. Other longer gaps were produced when approximate weekly "tipping curve" calibrations were performed. These were always accomplished during fair weather so no liquid water episodes were interrupted.

c. Acoustic Sounder. - An AeroVironment Model 2000 doppler acoustic sounder was utilized to obtain continuous vertical profiles of wind direction and speed. These data were collected primarily to assist in calculation of cloud liquid water fluxes and for use in analysis of SF_6 tracer gas transport and dispersion investigations. The unit was provided by NAWC under contract to Reclamation. It was operated in a moderate-sized clearing near the radar and radiometer vans. The system used two antennas oriented at right angles to each other, which alternately generated a 1500-Hz sound burst and received that portion of the sound burst reflected by turbulence and thermal microstructure discontinuities in the atmosphere. The doppler shift in the reflected sound was processed to provide horizontal windspeed and direction values in ascending 30-m bins up to 600 m above the ground. The processor was operated to provide 15-minute averages of the wind values in each bin. Due to the small size of the clearing available, sound reflecting from trees and other obstacles was a frequent problem in the first 7 bins [30 to 210 m a.g.l. (above ground level)], often resulting in invalid data. Reliable data were obtained above these levels much of the time, except with winds greater than about 10 m s^{-1}, when data quality was often degraded.

The controller/data processor unit and associated 9-track tape drive were located in the radiometer van and connected by cables to the transmitter/receiver unit located about 75 m to the south. The controller/processor unit contained a printer and keyboard, which were used for calibrations and monitoring real time data. The unit was operated continuously throughout the program with no failures.

d. Ice Particle Imaging Probe. - Ground measurements of ice crystal sizes, shapes, and concentrations were made using an aspirated Particle Measuring Systems, Inc. 2D-C optical array probe system. This laser imaging probe, with associated fan-aspirated sampling system, was operated in a small forest clearing approximately 100 m north of the radar and radiometer vans. Bulk snow samples were collected periodically adjacent to the sensor to establish the snowfall rate, and an anemometer was operated at sensor height to record the local winds. The microcomputer-controlled data operating and recording system was located in a small trailer nearby. Raw data were recorded on 9-track tape. The trailer additionally housed a photographic cold room where periodic 35-mm photographs were taken of ice crystals, which had settled on chilled glass plates during a known interval. These pictures provided an independent sample of crystal characteristics for comparison with the data provided by the imaging probe.

The ice particle data were collected to provide insight into the precipitation processes occurring. Knowing the crystal types, sizes, and concentrations, much can be inferred about the microphysics of the storms. This was particularly true when the ground data were collected simultaneously with aircraft observations above the site.

An attempt was made to operate the imaging probe almost continuously through all major storms; this was largely successful. However, some situations occurred where surface temperatures were above freezing and rain or partially melted snow were observed. This resulted in an incomplete data set on crystal characteristics. The unit was checked by the technicians at least hourly during storms, and bulk snow samples and crystal photographs were usually taken at these times if precipitation was solid state (not melted). The imaging probe operated throughout the season with no equipment failures.

e. High Resolution Precipitation Gauge. - A high-resolution precipitation gauge was operated in a small protected clearing approximately 150 m north of the radar and radiometer to provide sensitive time-referenced measurements of precipitation. The unit used a Belfort Instrument Company Model 5-780 dual-traverse weighing mechanism equipped with a specially fabricated 45.4-cm-diameter orifice and collection pan. The orifice area was five times larger than the standard area and provided a precipitation resolution of 0.05 mm water equivalent. Data were recorded on strip charts using a battery-powered clock equipped with daily rotation gears. This provided approximately 5-minute time resolution on precipitation events. The gauge was installed on a stand equipped with an Alter-II type windshield to minimize catchment errors associated with wind effects.

The unit was carefully calibrated both pre- and postseason and showed no significant deviation from a linear calibration.

Gauge service to change the antifreeze/oil solution and the recording chart was performed on a weekly basis and more frequently when required by large precipitation events. The unit operated reliably throughout the season and produced 99.2 percent fully valid data. The one small portion of missing data occurred when the gauge capacity was exceeded during an unusually large precipitation event on February 24, 1987. It was possible to accurately estimate the missing data by using the hourly bulk snow sample data collected near the gauge so a complete record for the entire season was available. The strip chart data were manually reduced in 1-hour increments and entered into the computer data base at Montrose following the field efforts.

f. Supporting Meteorological Data. - Data were collected from a variety of standard meteorological sensors through use of two automatic weather recording stations. The stations, known as PROBE (Portable Remote Observations of the Environment) units, utilize a data collection platform manufactured by Handar, Inc., to sample, average, and temporarily store the data. Once an hour, the units transmitted the 5-minute averaged data to a downlink at the Denver Federal Center by satellite relay. The data were then transferred to the Montrose computer by land line for quality checking and processing.

One station was located at the radiometer and provided atmospheric pressure from a Setra transducer, air and dewpoint temperatures from an EG&G Model 220 environmental monitoring system, as well as liquid and vapor values from the radiometer. The EG&G system was routinely calibration checked using an Assmann psychrometer and the Setra pressure by comparison to a precision standard. Data collection from all sensors on the station started on January 28, 1987, and continued almost uninterrupted for the remainder of the season. Occasional data gaps of 1 to several hours were experienced, mostly due to problems with the satellite transmission link.

The second station collected data from a group of sensors mounted on a radio communications tower located on a small hill just west of the Long Valley District Ranger Station. Commercial power was available at the site. Parameters measured were relative humidity, wind direction from two independent sensors, windspeed, and occurrences of icing events. The primary wind sensors (speed and direction) were electrically deiced units manufactured by Hydro-Tech, Inc. These were installed at approximately the 30-m level on the tower or about 5 m above the highest treetops. Due to an unknown restriction on the data collection platform signal input, the windspeed data were truncated above 10 m s^{-1}. However, speeds greater than this were relatively rare. The second wind direction sensor, manufactured by Meteorological Research, Inc., was located just below the Hydro-Tech units. This sensor was not deiced but provided more sensitive measurements of the short-term directional fluctuations. Icing occurrences at the tower were rare so valid data were obtained most of the time. Icing events at the tower level were documented using a Rosemount ice detector system. All parameters were measured almost continuously beginning January 26-28, 1987, with some short-term gaps experienced due to occasional difficulties with the satellite transmission link. Wind vane calibrations were performed using optical surveying equipment oriented to true north via solar angles.

g. Pibal Observations. - Pibal (pilot balloon) observations were routinely conducted in the early morning and late afternoon to obtain windspeed and direction profiles. The data served as a cross check on the accuracy of the acoustic sounder and as a check on the radar measurements of base height when the balloon was observed entering cloud base. A small shelter was installed in an open area near the acoustic sounder unit. This served as an inflation shelter and housed the Warren-Knight balloon-tracking theodolite. Balloons were inflated to a known amount of free lift (100 g), which produced a 2.8 m s^{-1} ascent rate. After release, the balloon was optically tracked for up to 20 minutes if conditions permitted. Horizontal and vertical angles were recorded at the end of each minute of flight. Vertical profiles of windspeed and direction were calculated after the season using a program developed for the Montrose computer.

h. Facilities and Personnel. - The Happy Jack site was staffed with two full-time employees who worked as field technicians. Supplementary personnel were available on an as-needed basis from the other sites to perform specific functions, such as maintenance of electronic equipment. The lead field technician, provided by NAWC under an ongoing contract with Reclamation, resided at the Long Valley District Ranger Station in a mobile home provided by the USFS under the Interagency Agreement with the Coconino National Forest. This individual monitored, operated, serviced, and maintained much of the equipment at the site; serviced the network of precipitation gauges; and performed much of the training for the second technician. The second technician was a resident USFS employee who was provided to the project on a cost-reimbursement basis. This individual was trained to perform the same basic duties as the lead technician. Two individuals were needed as operations were frequently conducted 24 hours per day.

i. Communications. - Both telephone and voice radio communications were provided at the Happy Jack site. Telephones were installed in the radar van and in the mobile home used by the lead technician. A leased voice radio system provided ground-to-ground communications from the radar to the Prescott and Camp Verde sites. A ground-to-air voice communications link was also available from the radar to the research aircraft using a Reclamation radio system. No communications equipment problems were experienced during the program.

3.1.2 Camp Verde Site. - The Yavapi-Apache Recreational Vehicle Park near the town of Camp Verde (see fig. 2-1) was used as the project rawinsonde site. The location was upwind of the Mogollon Rim for all storms with a westerly flow component and enabled the collection of data in the area of orographic uplift. The observations (soundings) consisted of radiotracking of a balloon-borne instrument package, which transmitted data to produce vertical profiles of atmospheric temperature, moisture, pressure, and wind. These data were taken to supplement NWS synoptic network soundings (e.g., at Tucson and Winslow) and for possible later input into atmospheric models to estimate seeding potential. Rawinsonde releases were routinely made at 0500 and 1700 to correspond to the NWS observation schedule; rawinsonde releases frequently were made at additional intermediate times to provide local information during storm events. The equipment, personnel, and facilities used are summarized below.

a. Equipment. - A WeatherMeasure RD-65A rawinsonde tracking station was used to track and record data from precalibrated rawinsondes. Each minute, the unit automatically tracked the instrument package and printed values of elevation and azimuth angles on a paper tape while the remaining data were continuously recorded on an analog strip chart recorder. Data were routinely taken from the surface to the 200-mb level. After the flight, the operator reduced the analog chart record in accordance with standard procedures (Federal Meteorological Handbook No. 3) and manually recorded the data in a standard format. The data were then sent to Montrose for computer entry, processing, and quality control checking. Some problems were experienced with defective sondes early in the season, but these were alleviated when a shipment of new units was received in early February. One brief equipment outage was experienced due to rainwater shorting a cable to the antenna assembly; this situation was easily rectified. Additional equipment used consisted of standard balloon filling devices.

b. Facilities and Personnel. - A husband/wife team provided by NAWC functioned as the equipment operator and launch assistant. They lived on-site in a leased camper trailer. The RD-65A equipment package was contained in a separate small trailer located directly adjacent to the living quarters. Supply storage and balloon inflation were accomplished in a leased hangar at a private airport approximately 100 m from the equipment trailer.

c. Communications. - The site was equipped with both telephone and a leased ground-to-ground radio system to provide communications to both the Prescott project headquarters and the Happy Jack site.

3.1.3 Payson Site. - A location at the Payson airport (see fig. 2-2) was used to operate a time-lapse camera. This unit provided a daytime visual record of clouds and storm systems occurring over the Mogollon Rim north of the site. Equipment and facilities were as follows:

a. Equipment. - An Automax 16-mm time-lapse camera system was used to obtain the photographic records. The unit was housed in a specially fabricated enclosure that protected it from the weather. The enclosure also contained timers to control the daily period of operation (0730 to 1840) and the frame interval and a time/date display that was recorded in the pictures. The camera was operated at a rate of one frame per 2 minutes. A complete data record was obtained with no equipment outages.

b. Facilities and Personnel. - The camera enclosure was installed on the roof of one of the airport buildings. The airport manager provided both the site and the electrical power to operate the equipment at no cost to the project. Film changes were necessary every 10 days, and this service was accomplished by the lead technician from the Happy Jack site.

3.1.4 Precipitation Gauge Network. - Precipitation gauges were operated at a total of seven sites as indicated on figure 2-2. Data were collected to provide information on storm precipitation amounts and intensities and spatial variability. Data could also be analyzed to determine if a statistically strong relationship existed between an upwind control site and gauges in the potential cloud seeding target area. Equipment, facilities, and personnel used were as follows:

a. Equipment. - Belfort Model 5-780 dual-traverse weighing mechanisms were used exclusively. With the exception of the high-resolution unit at Happy Jack (previously described), all were equipped with 28.7-cm-diameter orifices rather than the standard 20.2-cm-diameter orifices; this reduced their capacity to 15.25 cm but yielded a high measurement resolution of 0.13 mm water equivalent. All units used battery-powered clocks and analog weekly rotation strip charts as the recording medium. Each gauge was located on a stand in a small forest clearing and was equipped with an Alter-II type windshield to minimize catchment errors due to wind effects. For increased reliability, a pair of gauges was operated at the site furthest east (Willow Springs Lake Road). An antifreeze solution was used in the catch buckets to convert the falling snow to liquid, and an oil film retarded evaporation between storms.

Prior to the start of the program, all gauge mechanisms were carefully calibrated at the Montrose facility. Network installation and final onsite calibrations were performed by NAWC personnel in early December 1986. At that time, the gauges were capped and placed in a standby status until the start of the measurement program. Network activation was completed on January 11, and routine data collection continued through March 17, 1987. End-of-the-season checks disclosed no significant shifts in calibrations for any of the units. The gauges were highly reliable with 99.5 percent valid data collected. The missing data were generally due to periods of obvious partial capping of the gauge orifices during intense storms. Estimates based on accumulations in nearby gauges were made for these periods so a complete record was generated for the entire network.

b. Facilities and Personnel. - Gauge service and initial reduction of chart records were accomplished by NAWC personnel. Service trips to the gauges were made during clear weather periods on about a weekly interval. The lead technician at Happy Jack was mainly responsible for service but was occasionally assisted by the NAWC supervisor based in Prescott. The NAWC supervisor performed the bulk of the initial data reduction for 6-hour intervals and forwarded results along with the raw data records to the Montrose office. There the charts were independently read by Reclamation personnel, reading differences reconciled, estimates made for questionable data periods, and the entire data set entered into the computer data base for processing.

3.1.5 Prescott Airport Site. - Facilities at the Prescott airport (see fig. 2-2) were used both as the project headquarters and research aircraft base. The site offered an excellent airport equipped with an instrument landing system; hangar space; good availability of weather forecast information through the FAA Flight Service Station; as well as office, shop, and storage space made available by the USFS. The primary equipment, facilities, and personnel stationed at the site are discussed below.

a. Equipment. - The primary item of equipment at the site was the research aircraft. This was a highly instrumented Beechcraft King Air 200T turboprop, owned and operated by the University of Wyoming. The aircraft was pressurized, certified for flight into known icing conditions, and contained a full complement of instrumentation for cloud investigations. Reclamation provided the aircraft scientist, and NAWC provided the data system operator. A SF_6 detector system, provided through the NAWC contract, was operated on board the aircraft. Instrumentation on the aircraft is summarized in table 3-1.

Table 3-1. - Research aircraft instrumentation.

Parameter	Instrument type	Accuracy	Resolution
Temperature (total)	Platinum resistance	0.5 °C	0.1 °C
Temperature (reverse flow)	Platinum resistance	0.5 °C	0.1 °C
Dewpoint	Cooled mirror	0.5 °C *	0.3 °C
		1.0 °C **	
Heading	Magnetic	1.0 deg	0.1 deg
Altitude	Pressure	4.0 mb	0.3 mb
Altitude	Radar	2.4 m or 1%	0.07 m
Indicated air speed	Differential pressure	1.0 mb	0.1 mb
Rate of climb	Differential altitude IAS	1 to 2%	0.25 m s^{-1}
Position	VOR	1.5 deg	
	DME	0.4 km	0.2 km
	INS	1.0 km	0.1 km
Pitch, roll, vertical acceleration, ground speed, drift angle	INS		
Yaw, attack angles	Differential pressure	0.2 deg	0.1 deg
Turbulence	Pressure	10%	1%
Liquid water content (J-W)	Hot wire	0.2 g m^{-3}	0.05 g m^{-3}
Liquid water (CSIRO)	Hot wire	0.1 g m^{-3}	0.05 g m^{-3}
Liquid water (FSSP)	Laser optical		
Liquid water	Ice accretion		
Cloud droplet size	FSSP (laser optical)	2.0 μm	2.0 μm
Hydrometeor size and shape	1D-C (laser optical)	12.5 μm	12.5 μm
	2D-C (laser optical)	25.0 μm	25.0 μm
	2D-P (laser optical)	200.0 μm	200.0 μm
Time	Quartz	1 s day^{-1}	1 s day^{-1}
True air speed		0.5 m s^{-1}	0.1 m s^{-1}
Wind (horizontal):			
Speed		1.0 m s^{-1}	0.5 m s^{-1}
Direction		5.0 deg	1.0 deg
Vertical		1.0 m s^{-1}	0.5 m s^{-1}

* > 0 °C
** < 0 °C

The aircraft was used for two types of missions. The primary mission was to survey the spatial and temporal distributions of supercooled liquid water, ice particles, and winds over the research areas. The data collected provided a detailed but "snapshot" look at the three-dimensional distribution of the measured parameters; as such, the data complemented the more extensive continuous data sets collected by the ground instruments. The secondary mission comprised transport and dispersion experiments, which traced the spread of ground-released SF_6 gas to simulate seeding.

The aircraft flew 29 research missions and 3 crew training/familiarization flights for a total of 73.25 flight hours during the program period. Nine of the missions involved SF_6 detection. In late February 1987, the aircraft was unfortunately grounded for 3 days due to the closure of the Prescott airport during and following an unusually large storm. Aircraft reliability was excellent, with only a few relatively minor instrument outages experienced; these were corrected in the field.

The primary research investigations were conducted in area 2 (see fig. 2-2), which contained the Happy Jack site, with a few secondary efforts in area 3. No flights were made in area 1.

The flight profiles used for each mission type are described in detail in the project operations plan (Reclamation, 1987b) and are summarized as follows:

(1) Microphysical Missions. - Each mission started with an atmospheric sounding to 5.18 km m.s.l. (mean sea level) after departure from the Prescott base. This was followed by a descending series of along-the-wind passes over the research area being investigated. This series of measurements documented the vertical distribution of pertinent microphysical parameters in the air mass passing over a ground navigational reference point (generally the Happy Jack site). Following this, the aircraft made a 2.93-km m.s.l. "crestline" pass across the wind. This measured the uniformity of microphysical parameters along the crestline at the lowest permissible flight altitude. Additional series of along-the-wind and crosswind passes were subsequently performed as time and cloud conditions permitted.

(2) Transport and Dispersion Missions. - All releases of SF_6 were made from ground sites upwind of Happy Jack where good highway access existed. The determination of the appropriate release site for a given day was based on all available wind information. Releases were always made at relatively high elevation locations from which the plume was likely to be transported toward Happy Jack. The experiments sought to simulate ground-released seeding plumes.

Gas release was made at approximately 23 kg h^{-1} starting 30 to 60 minutes prior to aircraft takeoff. Aircraft measurements were made at as many downwind distances from the release site as practical. At each downwind distance, a number of passes were made approximately perpendicular to the wind direction at a series of stepped altitudes to document the vertical extent and cross-sectional shape of the plume. Releases were made during both VFR (visual flight rules) and IFR (instrument flight rules) weather. In the latter, the aircraft simultaneously collected microphysical data while conducting the tracing mission. Whenever possible, the VFR missions were flown when high- or mid-level cloud cover was present to minimize the effects of radiational heating or cooling at the surface.

b. Weather Forecast Data. - Complete weather forecast products were available at the FAA Flight Service Station located at the airport. Prescott is the hub Flight Service Station for Arizona and has a full complement of NWS prognostic products, satellite pictures, and current weather reports from all observing stations. Arrangements were made to utilize these products on a noninterference basis.

c. Facilities and Personnel. - The project headquarters was located in the USFS air tanker base facility at the airport. The building contained sufficient office space for all personnel, room for establishment of a project electronics shop, and storage space for supplies and miscellaneous equipment.

Overnight hangar space at a commercial facility was rented on an "as space available" basis through the aircraft contract. Only one hangar of sufficient size to accommodate the aircraft was available at the airport.

A crew of five persons was stationed at the site:

(1) Reclamation Site Coordinator. - The coordinator had the primary responsibility for daily field operations planning, coordination, and execution. Additionally, he served as aircraft scientist in charge of mission direction for all research flights.

(2) Reclamation Electronics Technician. - This technician was responsible for electronics maintenance, calibration, and repair of all Reclamation field equipment and also the aircraft instrumentation and data systems.

(3) NAWC Supervisor. - The supervisor performed daily operations coordination, personnel supervision, weather forecasting, data reduction and quality control, and general field support functions.

(4) NAWC Technician. - This technician functioned as the aircraft data system and SF_6 detector operator on all flights. He also maintained and routinely calibrated the SF_6 unit.

(5) Aircraft Pilot. - A University of Wyoming pilot was available to fly all missions.

d. Communications. - The site was equipped with both telephone and radio systems for communications with the other field facilities.

3.2 Early 1988 Field Instrumentation

All primary instrument systems other than a time-lapse camera were installed and operated at the Hannagan Meadow site (see fig. 2-1). The equipment complement consisted of the following:

a. Microwave Radiometer. - The same Reclamation radiometer system used at Happy Jack was utilized. The mode of operation was identical to the early 1987 operations. The unit's computer system gave considerable problems during the season, possibly due to the frequent commercial power fluctuations and failures that were experienced. Circuit board failures resulted in several periods of lost data.

b. Acoustic Sounder. - A new acoustic sounder system was purchased by Reclamation prior to the field season. The improved AeroVironment Model 2000 unit was operated approximately in the middle of a large forest clearing. The unit was configured to produce hourly averages of windspeed and direction in 35 vertical bins extending from near the surface to a maximum of 1050 m. The data recording and processing equipment was located in the radiometer trailer. The unit processed the data in real time using a microcomputer. The software package provided internal data quality checking. Data were recorded on floppy disks and later downloaded to the Montrose computer for processing. The unit was resilient to power failures and operated reliably throughout the field season.

c. Ice Particle Imaging Probe. - The same system as used at Happy Jack was located in a small protected forest clearing about 100 m north of the radiometer site. It was operated through as many storm events as possible, but many data interruptions occurred due to the frequent power failures. The system did not automatically "reboot" after a power outage, and personnel were frequently involved with higher priority duties after power failures. A component failure precluded gathering any data after March 2, 1988.

d. High-Resolution Precipitation Gauge. - A single gauge unit, equivalent to that used at the Happy Jack site, was operated directly adjacent to the ice particle imaging probe.

e. Supporting Meteorological Data. - Essentially the same sensors and PROBE data averaging and transmission system used at Happy Jack were operated at Hannagan Meadow. Sensors included the EG&G Model 200 temperature and dewpoint system, a Setra pressure transducer inside the radiometer van, and a tower-mounted wind vane and anemometer near the center of the large meadow. The wind sensors were 7 m a.g.l. Once again, all sensors were periodically calibrated against other standards (Assmann psychrometer, mercury barometer, and theodolite for wind direction).

f. Pibal Observations. - The same equipment and procedures were used at the Hannagan Meadow site as during the previous winter season. A total of 41 pibals were tracked on an intermittent basis during the field period.

g. Facilities and Personnel. - The site was staffed with one Reclamation representative during almost all storm periods (the site was abandoned a few times due to long power outages and consequent loss of heat). This scientist monitored the various equipment, performed calibrations, and took periodic weather observations. Of particular interest were the notes of ice crystals, which revealed that riming growth was frequent and confirmed the presence of supercooled liquid water.

Living facilities at the Hannagan Meadow site, located about 0.8 km off Highway 666, were rather spartan. A small camper trailer was located at the site for overnight accommodations during storms. Water, food, and other provisions were hauled in by snowmobile. Motel facilities in Alpine, about 37 km by road from Hannagan Meadow, were utilized for offduty periods. Commercial telephone service was available, and a USFS radio system served as an emergency communications backup.

4. ARIZONA STORM CLASSIFICATION

4.1 Introduction

Every storm that passes over a project area is unique. Both for forecasting and for cloud seeding, a storm must be treated as an individual with its own characteristics and challenges. Yet, there are some similarities that can be usefully summarized to give insights into the behavior of general classes of storms and general periods within storms. No classification system will ever be perfect. Each field season will bring some new characteristic to be considered. Nevertheless, the attempt at classification can be worthwhile for understanding general storm characteristics and evolution.

4.2 Synoptic Classes

As noted in section 1.2, Reclamation published a document entitled *Feasibility Study on Wintertime Cloud Seeding to Augment Arizona Water Supplies* (Reclamation, 1987a). This document attempted to identify the weather patterns that most favored the occurrence of wintertime precipitation over the Arizona mountains. Four general weather patterns were found that occur frequently and account for a substantial amount of the mountain precipitation. These are described in detail in Reclamation's report and are briefly summarized below:

A-1. - This type was characterized by the initial presence of a cold air mass centered over or near British Columbia, which was advected southward by a strengthening short wave aloft. As the air mass plunged southward, a closed circulation developed aloft, which frequently slowed its movement. Usually, a northeast-southwest cold front strengthened over the Nevada-Utah area and ultimately moved across Arizona. Precipitation, which was moderate to heavy, commenced and continued intermittently until after the front passed and drier air advected into the region. The key features of this weather type were the plunging cold air mass, the slow-moving circulation, and the availability of ample moisture from the Pacific Ocean.

A-2. - In this similar type, the southward plunge of the cold air mass occurred farther east; and the upper low did not cut off in time to substantially impact Arizona. Occasionally, the upper circulation did not close at all or closed well off the coast and then opened to a trough as the system moved eastward over land. A-2 did not advect moisture as well as A-1 and also moved faster. As a consequence, it generally produced less precipitation over Arizona.

B-1. - The third type was characterized by the presence of a closed quasi-stationary upper air circulation over western Canada with a trough over the Rocky Mountains and the western Great Plains. Short wave troughs moved from the northwest around the low, passed through Arizona, and brought intermittent precipitation lasting 1 to 2 days. Precipitation amounts generally ranged from light to moderate.

B-2. - The fourth type was similar to the B-1 system but generally differed in that the closed circulation in Canada was farther east than with B-1 and the upper flow was more zonal. Weak low-pressure waves passed around the southern portion of a high-pressure ridge (west of the Canadian low) and amplified somewhat after passing through the ridge.

The 1987 Reclamation report then went on to estimate the weather modification (cloud seeding) potential of these four weather types, which were considered to be the most frequent. But it must be realized that the inputs for the above classification system were climatological (daily) precipitation amounts, synoptic scale weather maps for the surface and 500 mb, and rawinsonde data for Winslow and Tucson. Such data cannot describe the microphysical characteristics of the clouds being considered.

It was attempted to classify all early 1987 and 1988 storms according to this system. The A-1 systems were the easiest to identify and usually produced the greatest amounts of precipitation. Some variations were noted in which the cold air made its southward plunge farther to the west than the description considers. However, many of the storms were difficult to assign to one of these four classes. Sometimes there was a sustained flow from the southwest in which upper air short waves were embedded. Some retrograding (westward moving) storms were found. The second field season revealed the important presence of flows of moisture from the intertropical convergence zone. These flows were detected mainly by satellite photographs. Much of the time, these flows arrived with no detectable surface features like a low or a front and with only a short wave for upper air support. The paucity of upper air data to the southwest of the United States made such systems undetectable with the current upper air network.

4.3 Synoptic and Cloud Classes

The 1987 field season produced considerably more data with which to evaluate and classify storm systems and estimate weather modification potential. The following were added to the observation systems used for the previous report: (a) high-resolution hourly precipitation records, (b) time-height and range-height radar displays, (c) 2-minute resolution CLW (cloud liquid water) and vapor data from the microwave radiometer, (d) satellite photographs, (e) time-lapse movies of the clouds, (f) aircraft microphysical, wind, and temperature data, (g) continuous recording of individual snow particles arriving at the ground, (h) hourly weather and icing rate from a tower on the Mogollon Rim, and (i) low-level winds from an acoustic sounder. These sources identified the basic cloud structures and the types of microphysical processes occurring in the clouds as well as the passage of synoptic scale systems. (The 1988 field season lacked the radar and aircraft observations.) Factors contributing to the seedability of the clouds could be examined with these new sources of data.

The next refinement in the classification scheme was developed for the Arizona storms observed during mid-January to mid-March 1987 and reported by Super and Boe (1988). A storm episode was defined by the nearly continuous presence of CLW over Happy Jack and/or hourly precipitation recorded by any gauge in a seven-gauge network, having no interval greater than 2 hours during which neither CLW nor precipitation was observed.

Entire storm episodes were categorized by two characteristics: the scale of the storm and the presence or absence of convection. Convection was identified by examining the following: radar time-height and range-height indicator plots, the character of the liquid trace recorded by the radiometer, aircraft observations when available, hourly weather reports from Flagstaff, time-lapse movies taken from Payson, stability parameters derived from Camp Verde rawinsonde observations, visual satellite imagery, and observations by the Happy Jack crew. Those storms clearly associated with synoptic scale features were so classified while the others were categorized as mesoscale. The mesoscale clouds were generally confined to the high topography of the Mogollon Rim. If an episode had noticeable convection present for half or more of its duration, it was classified as convective; otherwise it was termed stratiform. It was thereby recognized that an episode might contain both convective and stratiform periods, but the dominant type determined the classification.

Sixteen storm episodes were identified for the 1987 field season; ten episodes were designated SS (synoptic stratiform), three were SC (synoptic convective), and three were MC (mesoscale convective). MS (mesoscale stratiform) types were not observed to dominate an episode. Furthermore, there were several brief episodes of very limited duration where CLW and precipitation were not considered significant enough to be called a storm; these episodes were included in the NE (nonepisode) designation.

The Super and Boe (1988a) paper eventually combined the SS and SC episodes because of the similar behavior of the flux of CLW in those cases. The MC cases were then ignored because of their small number and different character. Such an outcome of the new classification system indicates that synoptic systems dominate the flux of CLW over the Mogollon Rim, just as the previous classification system identified the synoptic control of precipitation.

4.4 Episodes within Storms

Continued examination of the storms revealed that the character sometimes changed between types during a storm episode. The SS class contained diverse cloud forms (cirrostratus, altostratus, stratus, orographic stratus, or stratocumulus), downwind anvils, and embedded convection. Such clouds can be with or without the presence of CLW or precipitation.

The presence of high clouds (above 6 km m.s.l.), physically connected to lower clouds by particles producing a radar echo, generally indicated that CLW values would be suppressed. High clouds will frequently be colder than about -30 °C (contoured in the nighttime satellite infrared images). Analysts with Reclamation's SCPP (Sierra Cooperative Pilot Project) in California identified the "cirrus passage" (the advection of the rear edge of a high cirriform cloud band over the project area) as a frequent indicator of greater CLW values in the lower clouds (Reynolds, 1988). The same inverse correlation between cloud top height and CLW applies to the Mogollon Rim clouds, but there were exceptions in the observations of both field seasons. The nighttime hours of January 30-31, 1987, and the daytime hours of March 15, 1987, are important counterexamples.

The presence of high IPC (ice particle concentration) usually precluded the presence of abundant CLW. The ice particles rapidly grew and consumed the CLW. Such high concentrations are typically associated with periods in which the cloud tops are high. But again, exceptions (including the same two counterexamples) were found in the observations.

To determine if potentially seedable clouds occurred during any particular portion of a storm episode, the hourly precipitation and the hourly average CLW at the same site were integrated for each storm and plotted as a graph. Five examples, all 1987 storms, are shown in figure 4-1. For storm periods which had mostly precipitation and little CLW, the line plots nearly vertical; these periods had little seeding potential because the "fuel" for cloud seeding, the CLW, was essentially absent. During periods in which there was CLW but only trace precipitation, the line plots to the right; these periods were likely good candidates for seeding when the CLW was at least partially supercooled (< 0 °C).

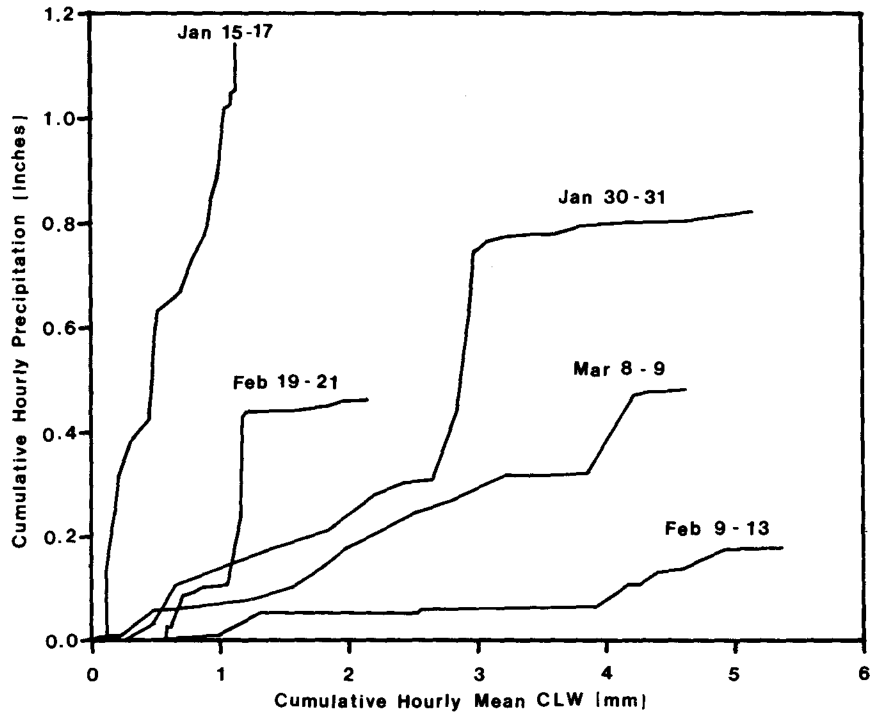


Figure 4-1. - The history of selected 1987 storm episodes as indicated by simultaneous integration of hourly averages of CLW and precipitation.

In figure 4-1, most lines move to the right before climbing, which indicates that, for the 1987 season and/or the Happy Jack region, periods of CLW without abundant precipitation often existed at the start of a storm episode. Such periods are particularly difficult to forecast. From the view of the satellites, cirriform canopies (opaque in the infrared satellite photographs) that preceded the episode masked indicators of the arrival of low-level moisture, which was responsible for the onset of CLW. Rawinsonde detection of the arrival of low-level moisture was inadequate with the density of observation sites and the 12-hour period between observations. The daytime visible satellite photographs indicated lower cloudiness only when the cirriform canopies were absent or transparent. Apart from the satellite predictors, the arrival of low-level moisture reverted to a "nowcast" based on observations by the microwave radiometer or visual observations of low clouds.

Line movement (fig. 4-1) towards the right is probably an indication of increased seedability. The detailed discussions of each storm episode in the appendix reveal that the 1987 SC and MC episodes were likely more seedable candidates than the SS classes. (There is uncertainty as to how much of the major MC episode was rain rather than cloud droplets; see section 8.) Wintertime convection can produce an abundance of CLW while being relatively inefficient in producing precipitation. Even though warmer than the stratiform clouds at the same altitudes; convective clouds may be particularly well suited for ground-based seeding. The convection, especially with solar heating, would probably have roots to the surface and would draw the seeding materials high into the clouds. (At least one SF_6 tracer experiment, described in section 9.5.6, may have involved sufficient solar heating of the Mogollon Rim slopes to rapidly lift the tracer high above the Mogollon Rim faster than in the more stable cases.)

Plots of 1988 storms indicated that the convective episodes and those involving tropical air tended to have more CLW and less precipitation than other storms. But the tendency of the 1987 storms to produce CLW prior to snowfall was generally absent at Hannagan Meadow. Only the large January 17-19, 1988 storm exhibited this characteristic.

The plots for all 1987 storms revealed a second tendency. Most episodes also had an abundance of CLW at the end of the storm. When these cases were examined in detail, it was found that the tall stratiform or convective clouds had already moved out of the project area. The winds or solar heating may still have been creating clouds, particularly over the high terrain; but the clouds were generally lacking in ice particles. The stratiform clouds were orographic, often under northeasterly winds, and were shallow. The cumuliform clouds most likely had surface roots from mechanical turbulence or solar heating. In all such cases, the clouds would be good candidates for seeding with ground generators if the artificial ice nuclei would reach sufficiently cold temperatures. The cases lasted many hours with measurable CLW so the ground-release strategy would have been less expensive than aircraft releases.

In the individual plots for all storms (only some are shown--see fig. 4-1), some lines moved diagonally upwards to the right for significant distances. Those were the periods during which both CLW and precipitation coexisted in moderate to large quantities typically with strong low-level winds with directions generally perpendicular to the Mogollon Rim axis. Sometimes such periods involved the apparent rapid condensation of CLW at low levels with abundant snow falling through it from higher levels. At other times, the periods had strong convective cells, which generated the CLW while the snow was falling in adjacent portions of the clouds.

Seedable conditions appeared to have existed at the start and the end of many episodes and sometimes within them. Those seedable conditions (in low altitude clouds) appeared to sometimes be targetable by ground-based seeding techniques, as discussed further in section 9.

Another technique used for identifying various cloud structures within a storm episode was to plot several observations together on the same time axis; this was done for all storms (an example is given in fig. 4-2). Examination of such plots, together with satellite photographs, observer notes, and all other available data, led to a classification of each hour of each storm by the SS, SC, MS, MC system. Tables 4-1 and 4-2 give the results of the hour-by-hour classification within the storm episodes for the 1987 and 1988 seasons, respectively. The times noted in the tables are the ends of each hour. Blank periods, while sometimes under

Table 4-1. - The hourly cloud system classifications for the 1987 field season at Happy Jack.

	0100	0200	0300	0400	0500	0600	0700	0800	0900	0100	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
1-15-87	---	---	---	---	---	---	---	SC	SC	SC	SC	SC	SC	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS
1-16-87	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SC	SC	SC	SC	SC	SC	SS	SS	SS	SS	SS	SS
1-17-87	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS
1-19-87	---	---	---	---	---	---	---	---	---	---	---	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS
1-20-87	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	---	---	---	---	---	---	---	---	---	---	---
1-23-87	---	---	---	---	---	---	---	---	---	SS	SS	SS	SS	SS	SS	---	---	---	---	---	---	---	SS	SS
1-27-87	---	---	---	---	---	---	SS	SS	SS	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
1-28-87	---	---	---	---	---	---	---	SS	SS	SS	SS	SS	SS	---	---	---	---	---	---	---	---	SS	SS	SS
1-29-87	SS	SS	SS	SS	SS	SS	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
1-30-87	---	---	---	---	---	---	---	---	---	---	SS	---	---	---	---	SS	SS	SS	SS	SS	SS	SS	SS	SS
1-31-87	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	---	---	---	---	---	---	---
2-4-87	---	---	---	---	SS	SS	SS	SS	SS	SS	SS	SS	SC	SC	SC	SC	SC	SC	SC	SC	---	---	---	---
2-5-87	MS	MS	MS	MS	MS	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
2-9-87	---	---	---	---	---	---	---	SS	---	---	---	---	---	---	---	---	---	---	---	---	---	SS	SS	SS
2-10-87	SS	SS	SS	SS	SS	SS	SS	SS	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC
2-11-87	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC
2-12-87	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	SS	SS	SS	SS
2-13-87	SS	SS	SS	SS	---	---	---	---	---	---	SS	SS	---	---	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC
2-14-87	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	---	---	---	---	---	---	---	---	---	---	---	---	---
2-15-87	---	---	---	---	---	---	---	SS	SS	---	---	---	---	---	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS
2-16-87	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	---	---	---
2-17-87	---	---	---	---	---	---	MS	---	---	---	MS	MS	MS	MS	MS	MS	MS	MS	MS	MS	SS	SS	SS	SS
2-18-87	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SC	SC	SC	SC	SC	SC	---	---	---	---	---	---
2-19-87	---	---	---	---	---	---	---	---	---	---	SC	SC	SC	SC	SC	SC	SC	SS	SS	SS	SS	SS	SS	SS
2-20-87	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SC	SC	SC	SC	SC	SC	MS	MS	MS	MS	MS	MS
2-21-87	MS	MS	MS	MS	MS	MS	MS	MS	MS	MS	MS	---	---	---	---	---	---	---	---	---	---	---	---	---
2-23-87	---	---	---	---	---	---	---	---	---	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS
2-24-87	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS
2-25-87	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS
2-26-87	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	---	---	---	---	---	---	---
3-2-87	---	---	---	---	---	---	---	SS	SS	SS	SS	---	---	---	---	---	---	---	---	---	---	---	---	---
3-6-87	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	SC
3-7-87	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	---	---	---	---	---	SC
3-8-87	---	---	---	---	---	SS	SS	SS	SS	SS	SS	SS	SS	SS	SC	SC	SC	SC	SC	SC	SC	SC	SC	SS
3-9-87	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	---	---	---	---	---	---	---	---	---	---	---	---
3-10-87	---	---	---	---	---	---	---	---	---	---	MC	MC	MC	MC	MC	MC	MC	---	---	---	---	---	---	---
3-15-87	---	SS	---	---	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SC	SC	SC	SC	SC	SC	SC	SC	SC
3-16-87	SC	SC	SC	SC	SC	SC	SC	SC	SC	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS
3-17-87	SS	SS	SS	SS	SS	SS	SS	SS	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC	---	---	---	---	---	---

SS = synoptic stratiform, SC = synoptic convective, MS = mesoscale stratiform, MC = mesoscale convective.
--- means that neither CLW nor precipitation were observed that hour.

Table 4-2. - The hourly cloud system classifications for the 1988 field season at Hannagan Meadow.

	0100	0200	0300	0400	0500	0600	0700	0800	0900	0100	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
1-16-88	—	—	—	—	SS	SS	SS	SS	SS	SS	SS	SS	SS	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC
1-17-88	SC	—	—	—	—	—	—	—	—	—	—	—	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS
1-18-88	SS	SS	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC
1-19-88	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	—	—	—	—	—	—	—	—
1-21-88	—	—	—	—	—	—	—	—	—	—	—	—	—	—	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS
1-22-88	SS	SS	SS	SS	SS	SS	SS	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1-30-88	—	—	—	SC	SC	SC	SC	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2-1-88	—	—	—	—	—	—	—	—	—	—	—	—	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS
2-2-88	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC
2-3-88	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	—	—	—	—	—	—
2-4-88	—	—	—	—	—	—	—	—	—	—	—	—	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS
2-5-88	SS	SS	SS	SS	SS	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2-17-88	—	—	—	—	—	—	—	—	—	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	—	—	—	—
2-18-88	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	SS	SS	SS	SS	SS	SS	SS	SS
2-19-88	SS	SS	SS	SS	SS	SS	SS	SS	SS	SC	SC	SC	—	—	—	—	—	—	—	—	—	—	—	—
2-25-88	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	SS
2-26-88	SS	SS	SS	SS	SS	SS	SS	—	—	—	—	SC	SC	SC	SC	SC	SS	SS	SS	SS	SS	SS	SS	SS
2-27-88	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SC	SC	SC	SC	SC	SC	—	—	—	—	—	—	—	—
3-2-88	—	—	—	—	—	—	—	—	—	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	—	—	—	—	—
3-3-88	—	—	—	—	—	—	—	—	—	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	—	—	—
3-7-88	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	SC	SC	SC	SC	SC	SC	SC	SC
3-8-88	SC	SC	SC	SC	SC	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

SS = synoptic stratiform, SC = synoptic convective, MS = mesoscale stratiform, MC = mesoscale convective.
— means that neither CLW nor precipitation were observed that hour.

the influence of a general synoptic storm system, had neither CLW nor precipitation observed. Yet this refined classification still does not clearly identify the periods of low to moderate height clouds, typically with a strong orographic component and abundant CLW, as good candidates for seeding. The radar patterns to be shown are highly useful for a more refined classification, but such data are not available for 1988 and are sometimes missing for 1987. Furthermore, satellite photographs could not always be used to identify the low wet clouds, like those at about 0600 on February 20, 1987 (fig. 4-2), because the cirriform cloud above would block the view.

A number of 1987 storm episodes will now be examined to illustrate within storm variability as well as some common features among storms. The first time period shown (fig. 4-2) is February 19-21, 1987, which portrays a varying cloud structure in a compact manner. The bottom of figure 4-2 plots the hourly precipitation amounts from the high-resolution gauge at Happy Jack. In the middle portion of the figure, the CLW is plotted, showing three general periods of liquid in the clouds above Happy Jack. In the upper panel, a time-height diagram of radar echoes (available for 1987 only) is plotted from the 5.4-cm radar operated at Happy Jack.

The radar echo plots (figs. 4-2 through 4-9) were constructed from range height indicator scans made to the north of Happy Jack every 5 minutes. The equivalent radar reflectivity factor was averaged for the 125-m by 1.0-degree range bins located within 2.2 to 3.3 km horizontal distance of the radar. This range was chosen to maximize radar sensitivity and minimize the ground clutter return. Data were not obtained in about the lowest 400 m above ground as the antenna elevation angle was kept above the treetops. Up to four levels of the equivalent reflectivity factor are shown on all radar plots. Any values exceeding 0 dBz are shown in black; those between -10 and 0 dBz are gray. The next lighter shading represents -10 to -20 dBz, and the lightest -25 to -20 dBz--the weakest echoes detectable with the particular radar system. While the greater dBz values generally indicate larger precipitation rates, the relationship can be complex for snow and ice particles as discussed by Smith (1984).

Figure 4-2 could include such variables as temperature, dewpoint, winds, and tower icing rates to show the passages of various synoptic features. Such variables were considered in the detailed storm analysis but were omitted from figures 4-2 through 4-9 for the sake of clarity.

The storm episode illustrated (fig. 4-2) lasted over 48 hours and was given an overall SS classification during the initial analysis, but the clouds were not purely SS. During this storm, a low and trough system over New Mexico retrograded into central Arizona and then resumed a southeastward movement out of the project area. After the passage of some low cirriform clouds, the episode began with the slow rise of cumulus clouds to the cumulonimbus stage from about 1000 to 1700 on February 19, 1987. CLW amounts varied considerably with time and exceeded 1.0 mm at 1445 and then rapidly diminished to almost zero as the radar echo intensified. The clouds were mostly confined to the higher terrain and therefore appeared to be under mesoscale control, but the satellite photographs showed enough neighboring clouds to suggest synoptic control. This period within the episode was then given the SC class.

The SS class was given to the period from 1700 on February 19 to 1200 on February 20, 1987. Until 0200 on the February 20, the clouds were basically stationary debris from the earlier convection that generated a snowfall containing aggregates at Happy Jack. Significant CLW existed for only about 1.5 hours and was

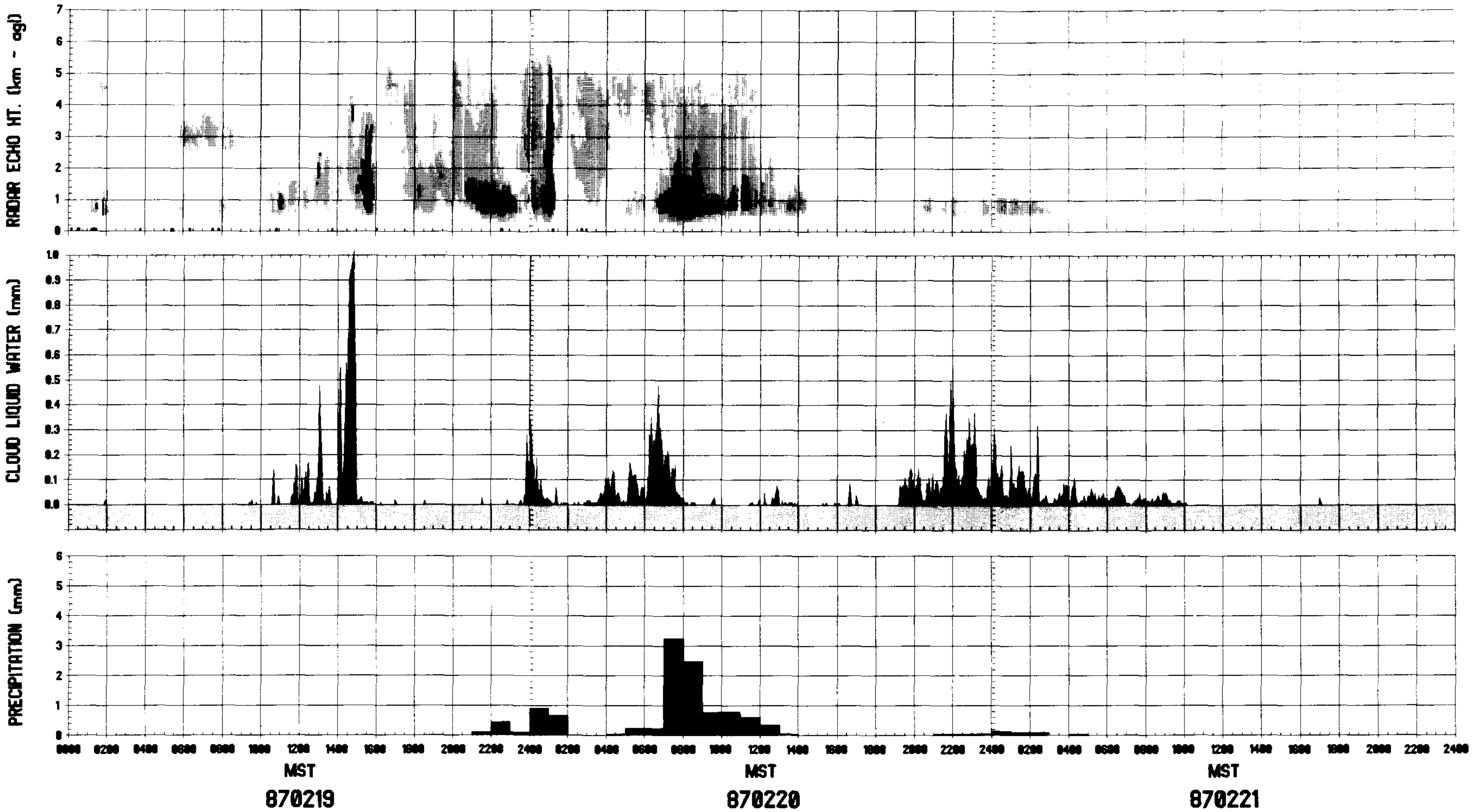


Figure 4-2. - The time history of precipitation, CLW, and radar echoes for February 19-21, 1987.

centered near 2400. The second half of the SS period was one in which the winds became easterly and an upslope cloud system was initiated. As the system intensified, CLW amounts increased until almost 0700. Then the high clouds became connected to the lower clouds and a heavy snowfall consumed the CLW.

After 1200 on February 20, 1987, the clouds became towering cumulus until 1800. The SC classification was again appropriate for this period; but the convection was not as tall as on the previous day and amounts of CLW were limited.

After 1800 on February 20, 1987, the low began to pass to the south of the project area and resumed a southeastward movement. Area winds shifted to strong northeasterly. The flow produced a low orographic stratus (upslope) cloud generally confined to the high terrain of the Mogollon Rim. This cloud was independent of the cirriform canopy of the low and so was classified as MS. The cloud system produced many hours of CLW and only trace precipitation, suggesting it was very suitable for seeding.

Figure 4-2 illustrates the general tendency (for which there are exceptions during other episodes) for clouds with tops under 6 km m.s.l. and not connected to higher cirriform clouds to have CLW. Abundant CLW existed at both the start and end of the episode as well as within it and always appeared in low clouds. In other episodes with the ending CLW period, the low clouds were usually of the SS and SC classes. There was frequently a classification problem in which the analyst had to choose whether to call a stratocumulus system as stratiform or as cumuliform. The choice was usually stratiform if the cloud elements in the time-lapse movies were densely packed together and had tops suppressed by an inversion or stable layer. During the nighttime, using the infrared satellite photographs that cannot resolve such cloud elements, the cumuliform class was selected if the low cloud field was lumpy in texture with clearings between some elements. But in practice, there was a continuous spectrum within the stratocumulus cloud type that made the analyst's criteria somewhat arbitrary for separating SS from SC.

There were other episodes in which the MS classification might have been used to indicate the presence of a major orographic contribution to the clouds at Happy Jack. The episodes were usually associated with high-speed, low-level winds and low-level moisture; but most of the episodes were surrounded by such a strong synoptic pattern of clouds that SS or SC classes were assigned.

In order to stress the individuality of the different episodes, additional figures, like figure 4-2, are presented and only briefly described.

Figure 4-3 illustrates the onset of CLW with the passage of the rear of a cirriform band. No precipitation was observed from the orographic altostratus-altocumulus cloud whose base was higher than the Mogollon Rim. It is seen that CLW appeared near 0830 on January 28, 1987, when the cloud mass first separated into unconnected lower and higher decks. By 1200, CLW still existed; but radar echoes were almost undetectable, indicating the absence of ice crystals in the cloud. This episode is further discussed in section 7, which deals with case studies.

An important counterexample, that of January 30-31, 1987, is illustrated in figure 4-4 and described in more detail in section 7 and the appendix. (A power outage after 0500 on January 31 interrupted the radar data for about 3 hours.) The appearance of an abundance of CLW from a low stratiform cloud at the end of the

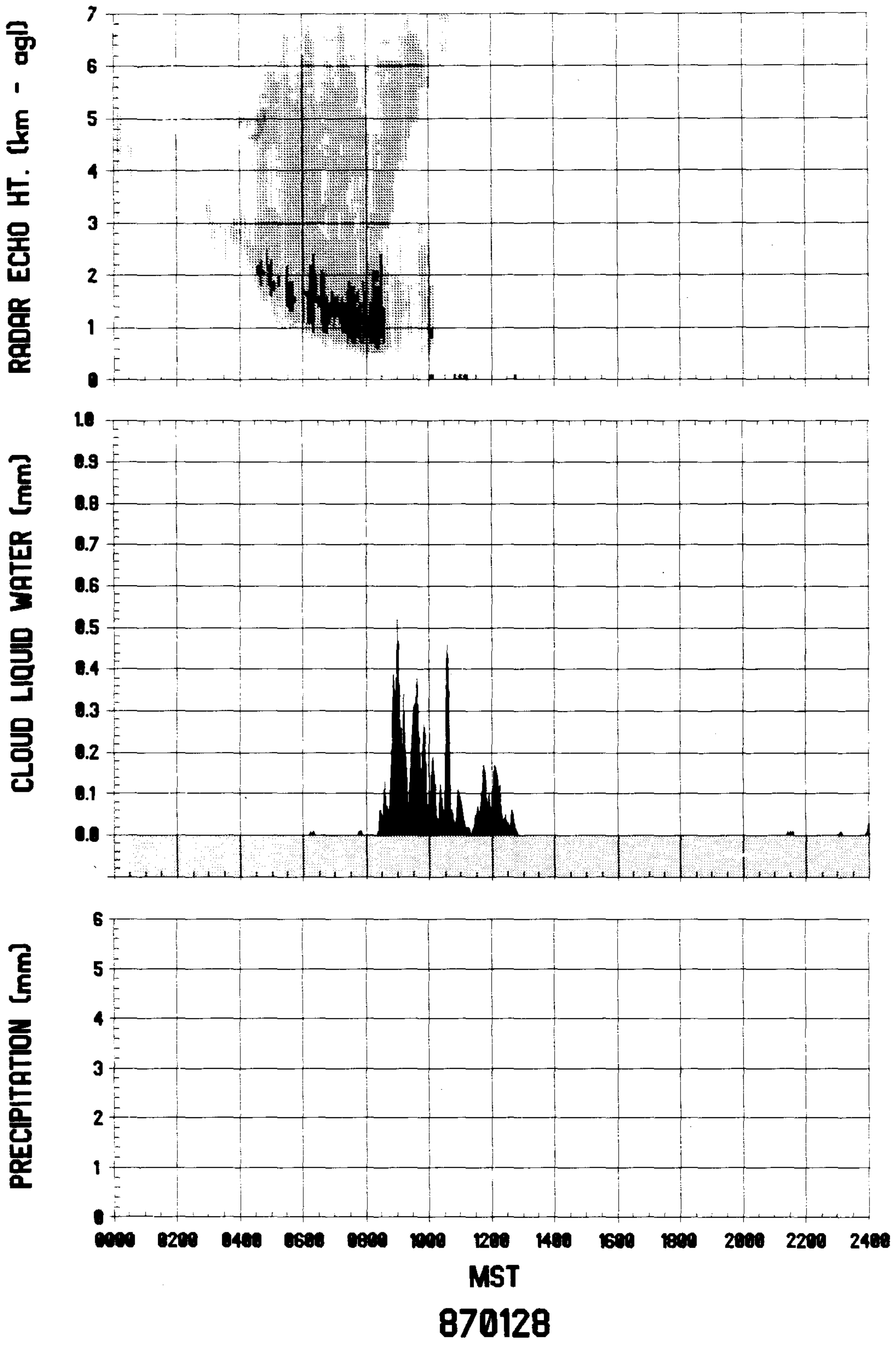


Figure 4-3. - The time history of precipitation, CLW, and radar echoes for January 28, 1987.

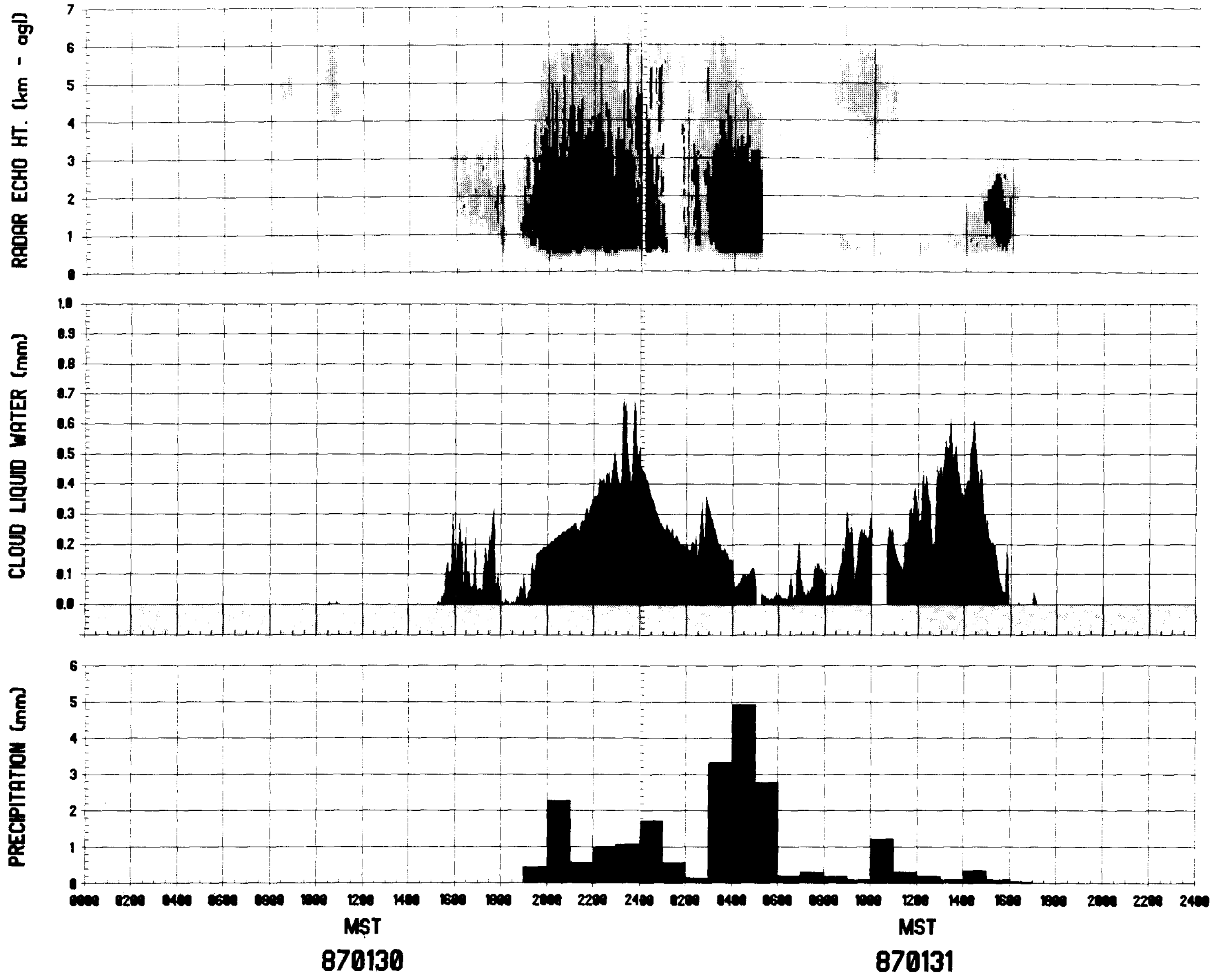


Figure 4-4. - The time history of precipitation, CLW, and radar echoes for January 30-31, 1987.

episode is illustrated well. But the unusual feature is the very pronounced CLW during the night hours when the radar tops were high and the precipitation rates were moderate. Strong flow over the barrier apparently produced more CLW than could be consumed by the falling ice particles.

Figure 4-5 presents an episode with no precipitation and generally weak low-altitude radar echoes. There were a few brief tall clouds late on February 15, 1987; but the clouds had only minor effect on the CLW. After 1000 on February 16, the radar was placed on standby status for the lack of significant echoes. But the CLW character changed to tall narrow spikes after 1000 on February 16 with the onset of towering cumulus and a change to the SC class.

The varied character of the storm that brought the largest snowfall to the region in several years is illustrated in figure 4-6. The episode began, as usual, with moderate CLW in low clouds and then changed to high CLW contents from clouds with moderate precipitation and radar tops of a middle height. The unusual presence of light CLW with high radar tops and extremely high precipitation rates is shown for the daytime hours of February 24, 1987. This illustrates that even heavy precipitation may not totally consume the CLW presumably being produced at low levels by the very strong winds then present (sometimes exceeding 17 m s^{-1} according to the acoustic sounder). Thereafter, the patterns are similar to those in figure 4-2 with high CLW amounts coexisting with shallow clouds.

The character of tall SC clouds is shown in figure 4-7. The CLW was present throughout most of the period and spiked strongly in the presence of the tall clouds, which brought the precipitation.

Figure 4-8 presents a series of systems. During the morning of March 8, 1987, the CLW and precipitation were from a low stratiform cloud. In the afternoon and evening, some strong convective elements were added. That episode ended with low CLW from a low stratiform cloud deck. The nighttime system between March 9 and 10 brought neither CLW nor precipitation. Finally, the brief MC system of orographically induced towering cumulus near midday on March 10 showed the increase in CLW and eventually some radar echoes. No precipitation was recorded at the Happy Jack gauge because of the scattered nature of the convection.

Finally, Figure 4-9 presents the patterns of the last storm of the 1987 field season and the counterexample of the presence of CLW with high radar tops and high precipitation rates for midday on March 15. The tall CLW spike after 1300 appears to be associated with a temporary decrease in cloud height. CLW, moderate precipitation, and moderately high radar tops were coexisting even during the subsequent night. The abundance of CLW at the end of the episode under low radar tops appeared again.

The appendix contains more detail about each storm episode. Additional comments are given on the 1987 episodes that were generated during the construction of table 4-1, and similar descriptions are included for the 1988 season. Some of the episodes or periods receive detailed attention in section 7 as case studies.

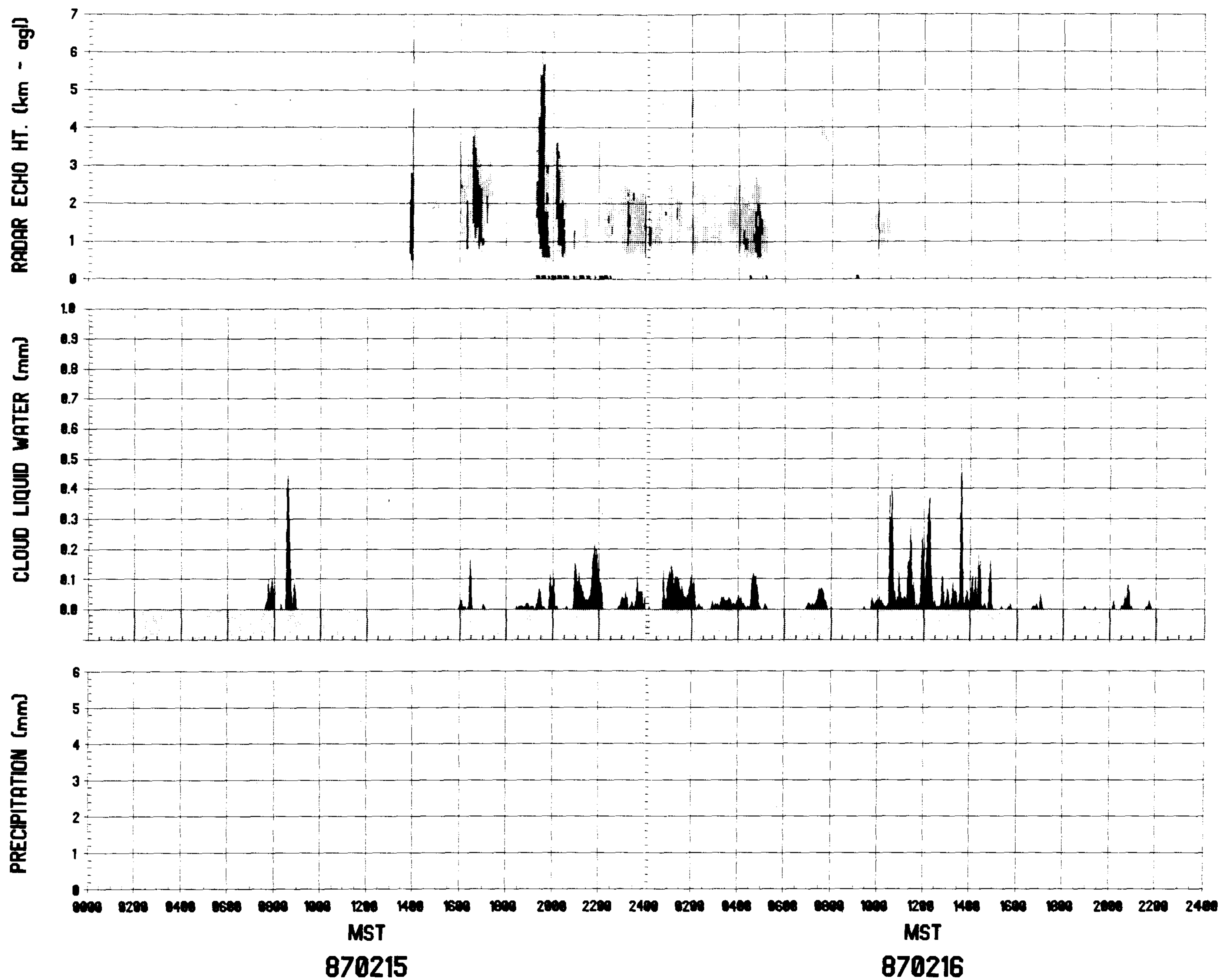


Figure 4-5. - The time history of precipitation, CLW, and radar echoes for February 15-16, 1987.

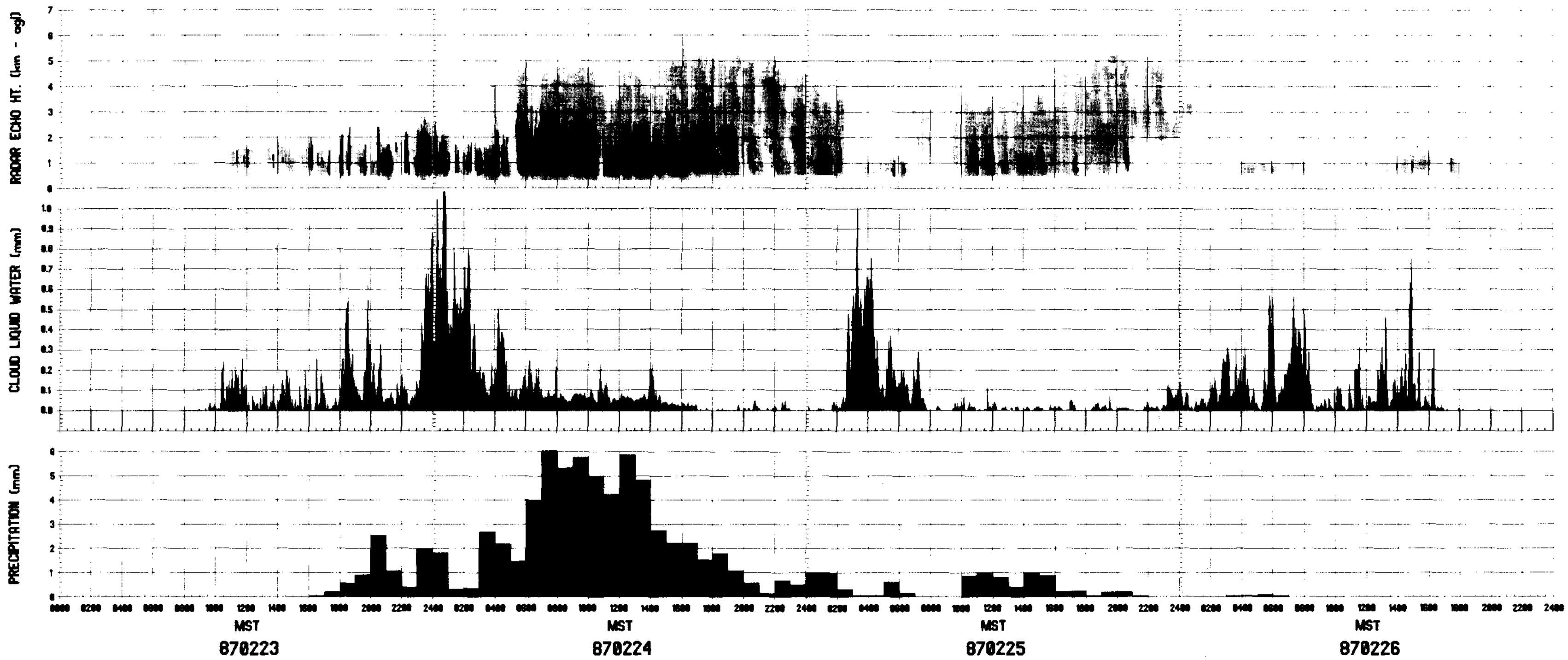


Figure 4-6. - The time history of precipitation, CLW, and radar echoes for February 23-26, 1987.

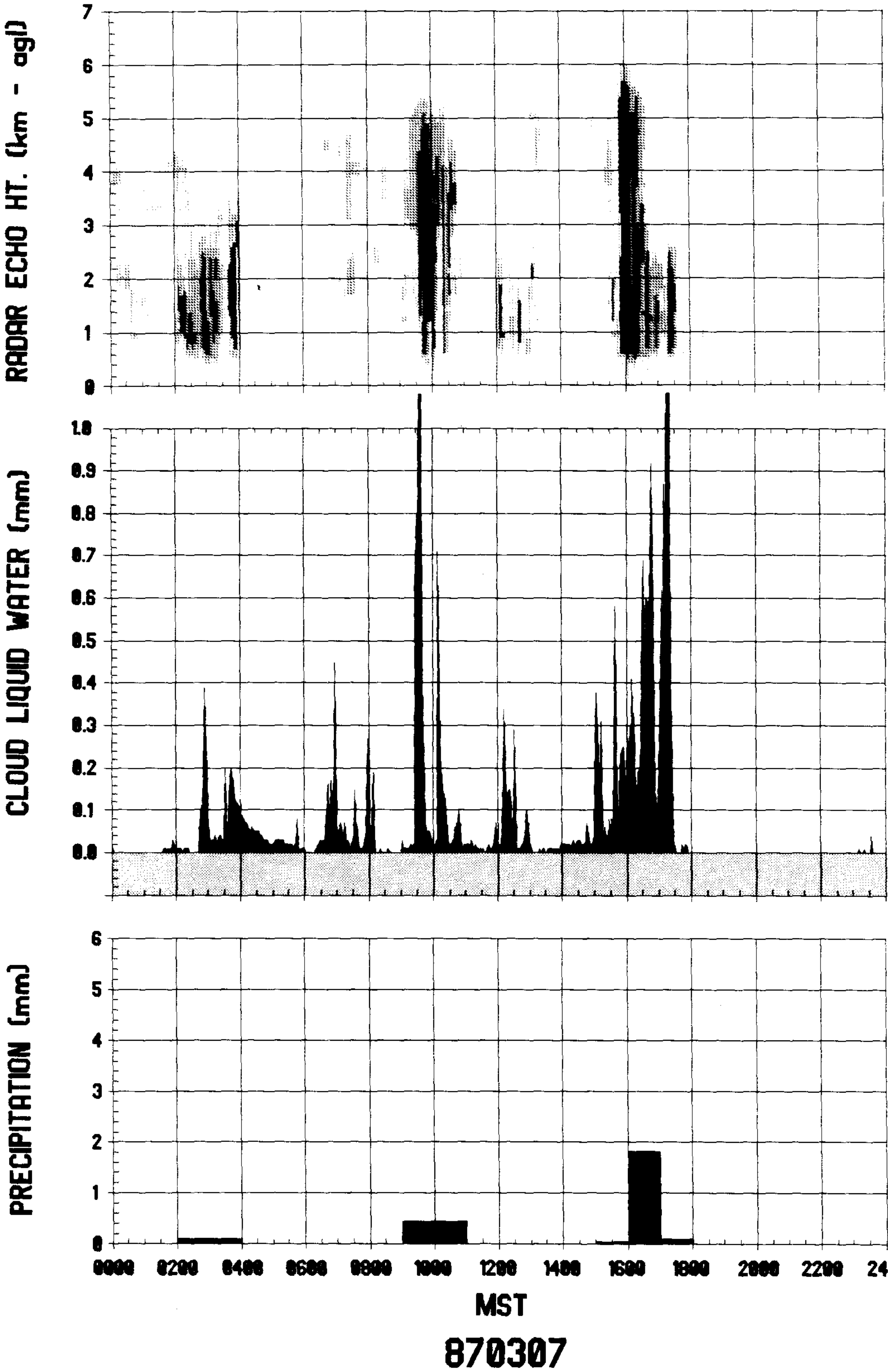


Figure 4-7. - The time history of precipitation, CLW, and radar echoes for March 7, 1987.

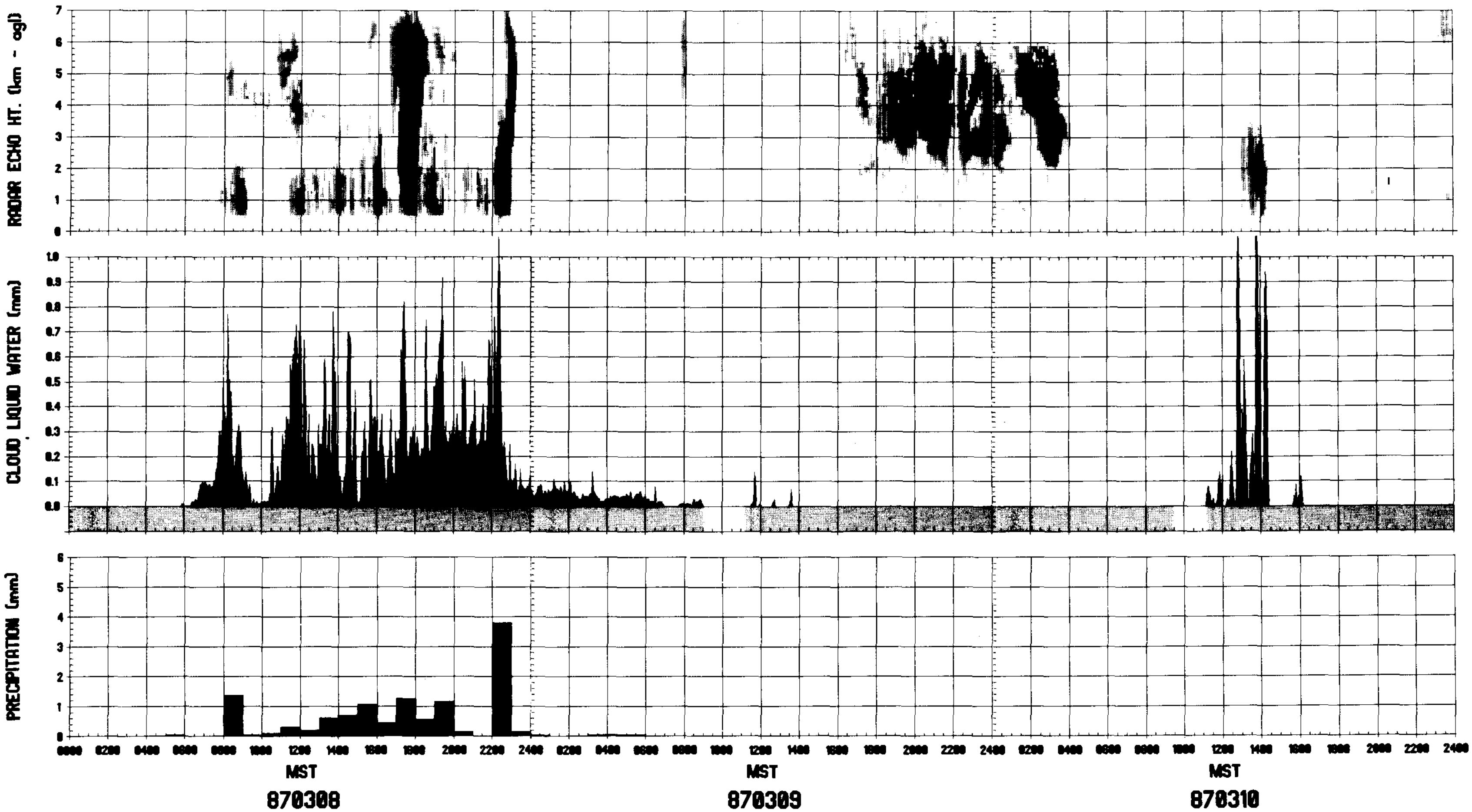


Figure 4-8. - The time history of precipitation, CLW, and radar echoes for March 8-10, 1987.

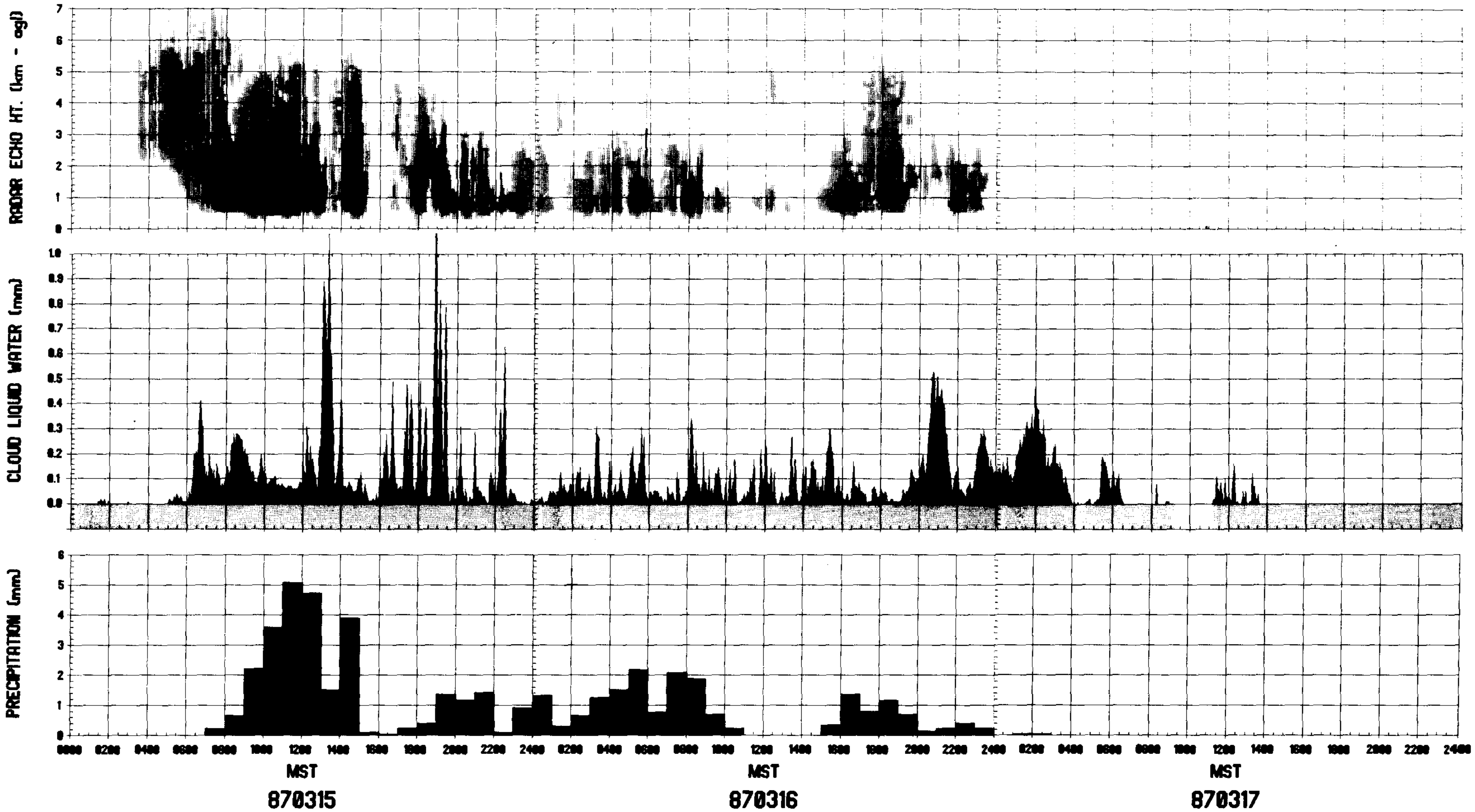


Figure 4-9. - The time history of precipitation, CLW, and radar echoes for March 15-17, 1987.

4.5 More on the Cloud Top Relation

The previous subsection presented many illustrations of the interactions between cloud (radar) tops and CLW, in addition to precipitation. Several features of these relations were reported for the Colorado mountains (Rauber and Grant, 1986; Rauber, et al., 1986).

As a final illustration of these relations, all radar plots, like those of figures 4-2 through 4-9, were examined to estimate the altitude of the tops of the lowest cloud deck. (Usually, there was only one deck of clouds.) This was a crude visual estimate, assigning each hour to a band of 0 (= no echo) and less than 1, 2, 3, --- 7 km a.g.l. Traces of higher tops that might have placed the hour into the next higher category were usually ignored in favor of the average tops. For convective situations, the tallest tops were usually chosen. For periods in which a high radar deck had bases descending towards a lower deck, the altitude band was not increased to the tops of the higher deck until there was a substantial interconnection between the two radar echo decks. Table 4-3 presents the altitude assignments for those hours with radar data but only those hours with either CLW or measurable precipitation also present at Happy Jack. The additional criteria eliminated the cirriform periods that have no modification potential.

Using the altitudes of table 4-3, nonzero hourly CLW averages, and nonzero hourly precipitation amounts at Happy Jack, figure 4-10 was constructed for all hours indicated in the table. The two curves were plotted against the altitude of the radar tops of the lowest cloud deck. The lower curve shows the cumulative percent of all hourly CLW averages. (A curve constructed with CLW flux was nearly identical.) Similarly, the upper curve shows the cumulative percent of all precipitation. It is seen that more than half of the total CLW observed was from clouds whose radar tops were about 2.5 km a.g.l. or less. But such shallow clouds produced only 12 percent of the precipitation. About 40 percent of the total precipitation was from clouds with radar tops at or below 4.0 km a.g.l. while 75 percent of the CLW was from such clouds. Precipitation and CLW contributions were limited from clouds whose radar tops were greater than 5 to less than 7 km a.g.l. Figure 4-10 shows that, for the 1987 field season at Happy Jack, there was an abundance of CLW associated with the presence of the lowest cloud decks and from which little precipitation fell. Such decks should be good candidates for cloud seeding.

Table 4-3. - The tops of the lowest deck of radar echoes during hours with either measurable CLW or precipitation.

	0100	0200	0300	0400	0500	0600	0700	0800	0900	0100	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
1-17-87	—	—	—	—	—	—	—	—	—	—	—	—	3	—	—	—	3	—	1	—	—	—	1	—
1-19-87	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	4	4	3	4
1-20-87	3	3	4	3	—	—	—	—	0	0	0	0	0	—	—	—	—	—	—	—	—	—	—	—
1-28-87	—	—	—	—	—	—	—	6	7	3	2	0	0	—	—	—	—	—	—	—	—	—	—	—
1-30-87	—	—	—	—	—	—	—	—	—	—	0	—	—	—	—	4	4	4	3	6	6	6	6	6
1-31-87	6	3	6	6	5	5	—	—	2	1	1	1	2	2	3	3	3	—	—	—	—	—	—	—
2-13-87	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2	4	2	2	6	2	3
2-14-87	3	3	2	2	3	4	3	3	2	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2-15-87	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	4	—	2	6	5	3	5	3
2-16-87	3	3	3	3	3	—	—	0	—	3	2	—	—	—	—	—	—	—	—	—	—	—	—	—
2-18-87	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	3	2	—	—	—	—	—	—	—
2-19-87	—	—	—	—	—	—	—	—	—	—	2	2	2	3	4	4	0	—	—	—	—	5	5	5
2-20-87	6	6	5	5	1	2	5	5	5	5	5	5	3	2	—	0	0	—	—	0	1	1	1	1
2-21-87	2	2	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2-23-87	—	—	—	—	—	—	—	—	—	0	2	2	2	2	2	2	2	2	3	2	3	3	3	3
2-24-87	3	2	3	4	4	5	5	5	5	5	5	5	5	5	5	5	6	6	6	6	5	5	5	5
2-25-87	5	4	4	2	2	2	2	4	—	4	4	4	5	5	5	5	5	5	6	6	6	1	0	1
2-26-87	1	0	0	1	2	2	2	2	1	1	1	2	2	2	2	2	2	—	—	—	—	—	—	—
3-6-87	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
3-7-87	—	2	4	4	0	0	0	3	3	6	5	2	3	3	1	6	6	3	—	—	—	—	—	0
3-8-87	—	—	—	—	—	0	0	2	2	2	0	2	2	2	2	3	3	7	4	3	2	2	7	7
3-9-87	0	2	0	2	0	0	0	0	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
3-10-87	—	—	—	—	—	—	—	—	—	—	—	—	—	4	4	0	0	—	—	—	—	—	—	—
3-15-87	—	0	—	—	—	6	7	7	5	5	6	6	6	5	6	4	5	4	5	4	3	3	3	4
3-16-87	4	4	3	3	4	4	4	3	3	2	2	2	2	1	2	3	4	5	5	5	3	3	3	3
3-17-87	0	0	2	2	0	0	0	—	0	—	—	2	2	2	—	—	—	—	—	—	—	—	—	—

Trace echoes were ignored.
0 means no echo.
1 to 7 means that the tops were generally < 1 to < 7 km a.g.l.
— means that no radar data were recorded (standby status or malfunctions) and/or that neither CLW nor precipitation were recorded.

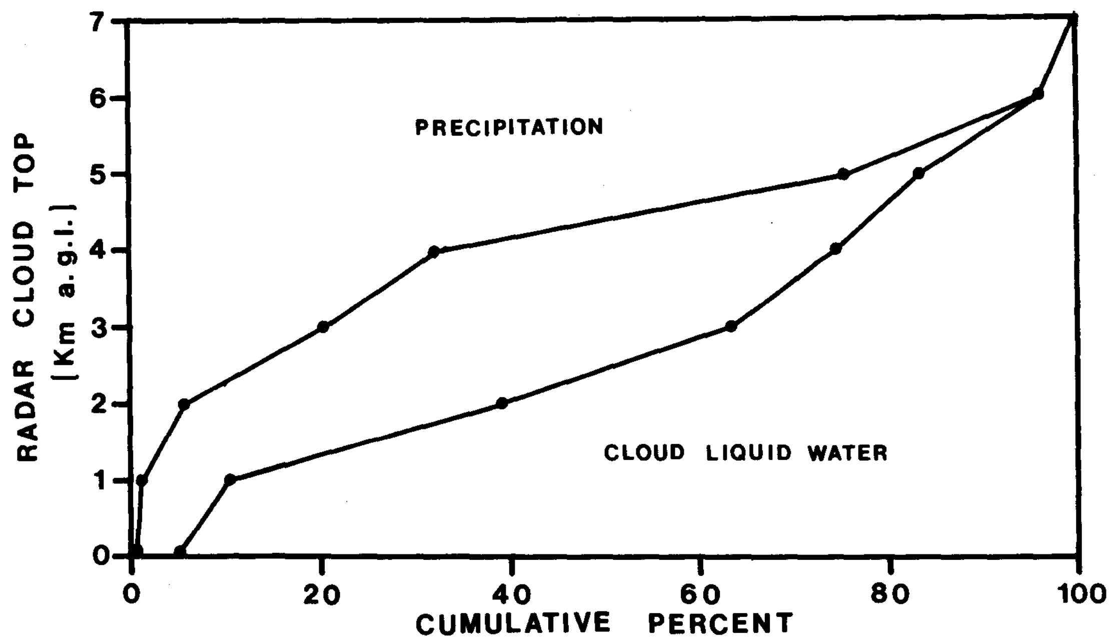


Figure 4-10. - The cumulative distributions of CLW and precipitation as functions of the depth of the lowest cloud deck above Happy Jack.

5. CLW INVESTIGATIONS

5.1 Introduction

It has long been recognized that SLW (supercooled liquid water) is the required "raw material" for augmentation of precipitation by seeding winter orographic clouds; that is, clouds over mountain barriers (for examples, see Ludlam, 1955; and Grant and Kahan, 1974). The SLW consists of tiny water droplets at temperatures colder than 0 °C, formed by condensation of water vapor from air cooled through lifting (as when forced to ascend mountain barriers).

The seeding of winter orographic clouds involves the conversion of some of the SLW into ice particles. Ice crystals grow rapidly in a supercooled water droplet environment because an ice surface has a lower equilibrium vapor pressure than a liquid surface at the same temperature. Unlike the tiny droplets, which are essentially suspended in the air stream, the much larger ice particles can settle to the mountain surface provided their growth and fallout are sufficient prior to reaching the zone of descending air normally found immediately downwind of mountain barriers (lee subsidence zone). The descent and warming of the air in this zone rapidly evaporate the water droplets and sublimate the ice crystals. Thus, successful cloud seeding often involves a "race" between the time required for ice crystals to form, grow, and fall to the surface, and the time available prior to evaporation in the lee subsidence zone. A detailed discussion of all physical processes involved is given by Dennis (1980).

The main point of this discussion is that the availability of SLW is a necessary condition for the existence of practical precipitation augmentation potential (seedability). Some additional but limited potential may exist in conditions between ice and water saturation, which will be ignored here. The amount of SLW that can be converted to snow on the ground will also not be considered in this section. Here, the concern is with the frequency of occurrence of SLW and its magnitude and duration. Also, the flow or "flux" of SLW over the barrier will be considered as this represents the absolute upper limit for precipitation augmentation potential.

It would be impractical for any cloud seeding program to convert all the seasonal SLW flux to snowfall because of constraints such as timely delivery of seeding agents to desired cloud regions, limited time available for ice crystal growth and fallout, suspension criteria imposed during abnormally wet periods, etc. However, if observations were to show the seasonal SLW flux to be only a very small percentage of natural annual streamflow from a region, the potential of seeding to augment the streamflow through increased snowfall would likewise be very limited on a percentage basis. Admittedly, even a small percentage increase in streamflow might represent a significant volume of water in some drainages. However, small percentage increases are difficult to demonstrate with confidence.

On the other hand, if the SLW flux was found to be a large percentage of annual streamflow, this would suggest a possible large potential for cloud seeding. Estimation of the actual potential would involve consideration of the various constraints already noted, and a seeding program would be required to demonstrate the seasonal precipitation increase practical to achieve. However, observation of SLW and its flux over a barrier is clearly a very important first step toward estimating seeding potential. While the importance of SLW flux has been recognized for many years, only recently has it been practical to routinely observe SLW flux. Development of the microwave radiometer (Hogg et al., 1983) has made possible continuous measurements of the integrated amount of liquid water above the instrument. When the liquid water is known to consist entirely of cloud droplets and not rain drops, it is referred to as CLW. When the CLW is supercooled, the radiometer measurements can be combined with windspeed and SLW flux estimates made as reported for the Grand Mesa, Colorado, by Boe and Super (1986) and Thompson and Super (1987). It will be shown that the large majority of CLW observations over the Mogollon Rim in early 1987 and early 1988 consisted of SLW. However, as not every measurement was totally supercooled, the more general CLW term will be used rather than SLW. CLW that is not supercooled can also enhance the growth of precipitation-sized particles falling through it.

5.2 Observations

Reclamation's microwave radiometer (hereafter referred to as radiometer) is described in section 3 and was operated on the Mogollon Rim from January 14 to March 17, 1987, and again from January 15 to March 10, 1988. During the 1987 field season, the unit was located at the Happy Jack Ranger Station at an elevation of 2290 m m.s.l. The same instrument was operated during early 1988 at Hannagan Meadow in the White Mountains at an elevation of 2790 m m.s.l. The radiometer was always used in a vertical-pointing mode to provide the integrated amount of CLW and water vapor passing directly above the unit. Radiometer data collected during cloud-free (and thus CLW-free) conditions were examined to determine the magnitude of the drift of the instrument. Much of the time the baseline drift was so slight as to require no correction at all. On a few days, the drift was sufficient to necessitate a correction of +0.01 to +0.03 mm, but care was taken to maintain a zero or slightly negative baseline for liquid water. Thus, in all cases with positive readings, CLW actually existed above the instrument. In addition, hourly mean values of CLW less than 0.01 mm have been ignored in the analyses discussed except where noted.

It is noteworthy that the work of Heggli et al. (1987), partially based on the radiometer used in this study, indicated that radiometer-measured values of water vapor were likely within 15 percent of actual values. Further, Heggli et al. showed that two similar radiometers operated near one another yielded very similar liquid and vapor measurements. The absolute accuracy of the liquid values was difficult to independently verify because of the lack of a suitable standard.

Both radiometer observing sites were chosen primarily because of location on the Mogollon Rim crestline, with electrical power availability and nearby roads as important secondary considerations. At both sites, the observations were just upwind of the crestline, in the prevailing southwesterly or westerly flow, so the flux estimates approximated the amount of CLW naturally available just prior to beginning depletion in the lee subsidence zone. This can be thought of as nature's surplus water, not converted to snowfall due to the inefficiencies of the precipitation process in the winter clouds.

The radiometer does not respond to dry snow in the atmosphere or on the reflector, but wet snow on the reflector can cause serious overestimates of both liquid and vapor (Hogg et al., 1983). Three brief periods with the wet snow problem occurred during the storm of January 30-31, 1987. Such occurrences were minimized by a large fan directed over the reflector together with frequent day and night checking and cleaning. The few problem periods were indicated by abrupt, several-fold increases in liquid and vapor values. Linear extrapolation from adjoining periods with valid data was used to estimate the CLW in these cases.

A more serious problem occurs when rain is present. While Hogg et al. (1983) used spraying tests to show a wet reflector has little effect on the readings, the presence of rain in the atmosphere above the unit can result in large increases in indicated liquid water. The radiometer is unable to distinguish between that liquid water due to tiny cloud droplets (of interest to cloud seeding potential) and that due to much larger rain drops. The mixed cloud droplet-raindrop situation was a problem during all or portions of three 1987 storms when the melting level was above the radiometer. These observations were not included in subsequent analyses. All other 1987 storms were believed to have only dry snow (unmelted) precipitation above the radiometer so CLW measurements were due to supercooled cloud droplets only. While some light rain occurred during a few 1988 storms, any increase in indicated CLW was found to be minor; therefore, no 1988 data were excluded.

5.3 Storm Typing

A classification scheme was developed for the Arizona storms observed during both field seasons as discussed in section 4. Briefly, a 1987 storm episode was defined by the nearly continuous presence of CLW over the radiometer at Happy Jack and/or precipitation from the seven gauge network, having no interval greater than 2 hours during which neither CLW nor precipitation was observed. The storm episode definition was slightly different in 1988. Only one precipitation gauge was available (at Hannagan Meadow) although precipitation observations were also used from the time-lapse camera at Alpine and occasional observer notes from off-duty field personnel staying there. The nearly continuous presence of CLW over Hannagan Meadow and/or precipitation observed at Hannagan Meadow or Alpine were used to define storm episodes in 1988, similar to the 1987 approach but with more localized precipitation observations. Further, problems with electrical power outages and/or computer malfunctions resulted in a number of periods with missing radiometer data in 1988.

Storm episodes were categorized by two characteristics: the scale of the storm and the presence or absence of convection. As discussed in section 4, the latter was estimated for each hour of each storm episode based on examination of all available data. Those storms clearly associated with synoptic scale features (observed on weather maps and/or satellite photographs) were so classified while the others were categorized as mesoscale.

Each hour was classified into one of the four possible classes (SS, SC, MS, or MC; see sec. 4.3). Table 5-1 shows the distribution of all hours of radiometer data with mean values of at least 0.01 mm in each class for each field season. A total of 63 hours were not included because of known or suspected rain above the radiometer.

Table 5-1. - Number of hours with mean CLW amounts of at least 0.01 mm for each season and storm class.

Year	SS	SC	MS	MC	Total
1987	199	62	23	33	317
1988	32	55	0	0	87

It is seen that observations of CLW were about 3.6 times as frequent during early 1987 as during early 1988. This is believed to be due primarily to more frequent storm conditions during the initial field season as suggested by 257 hours of measurable precipitation at Happy Jack compared with 190 hours at Hannagan Meadow, a higher elevation site. The significant loss of radiometer data at Hannagan Meadow was also a factor. Considerable additional data would be required before it could be determined whether significant differences in CLW actually exist between Happy Jack and Hannagan Meadow on a long-term basis. The differences shown in table 5-1 are likely due to more frequent storminess during early 1987.

5.4 Temporal Distribution of CLW

5.4.1 Frequency Versus Amount. - The frequency distributions of hourly mean amounts of vertically integrated CLW were examined for each storm class observed over Happy Jack and over Hannagan Meadow. No significant differences were apparent in the shapes of the distributions. The highest amounts of CLW were associated with the synoptic scale episodes. However, mesoscale cases were far less frequent so occasional high values may not have been sampled (only one mesoscale episode occurred during 1988, but radiometer data are missing). Maximum hourly mean CLW amounts were near 0.5 mm for both SS and SC cases during both field seasons. The maximum amount for MC cases at Happy Jack was between 0.30 and 0.35 mm and that for MS cases was between 0.15 and 0.20 mm.

Because of the similarities in the shape of the distributions, the SS and SC hours have been combined in figures 5-1 and 5-2 for 1987 and 1988, respectively. Approximately 40 percent of all hours are between 0.01 and 0.05 mm in both figures (hourly means < 0.01 mm were ignored). Hourly means greater than 0.20 mm occurred in 14 percent of the 1987 cases and 24 percent of the 1988 cases. Median amounts at both Happy Jack and Hannagan Meadow were slightly less than 0.1 mm. Comparison of the two figures suggests CLW amounts were quite similar over the two sampling locations located about 225 km apart. It is speculated that similar distributions would be found over much of the Mogollon Rim.

To put these values into perspective, a cloud of 1 km vertical extent with uniform CLW content of 0.1 g m^{-3} would yield a vertically integrated liquid water amount of 0.1 mm. This suggests that most hours with CLW over both sites had clouds with low mean liquid water contents; that is, a few hundredths to one or 0.2 g m^{-3} of air. Aircraft observations over Happy Jack usually showed values in this range (see sec. 6). Such values are typical of winter orographic clouds at a number of locations in the Rocky Mountains (Cooper and Marwitz, 1980; Rauber and Grant, 1986; Super and Heimbach, 1988). The low CLW amounts translate into relatively low flux values with typical windspeeds. However, the seasonal flux and possibly the seeding

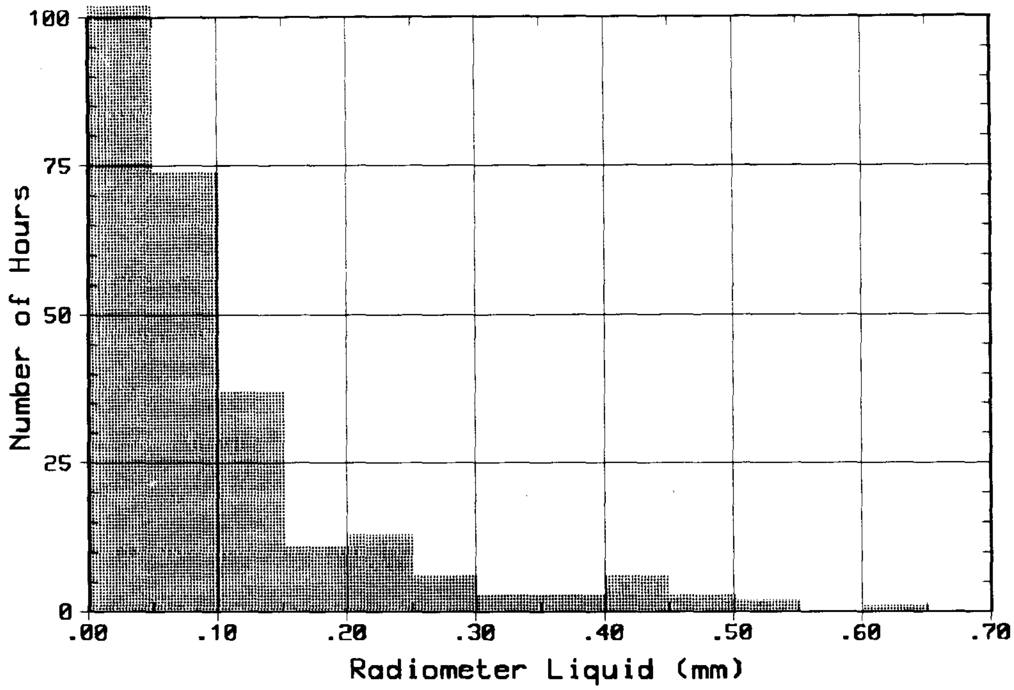


Figure 5-1. - Distribution of 217 hourly means of vertically integrated CLW amounts for SS and SC classes over Happy Jack during early 1987.

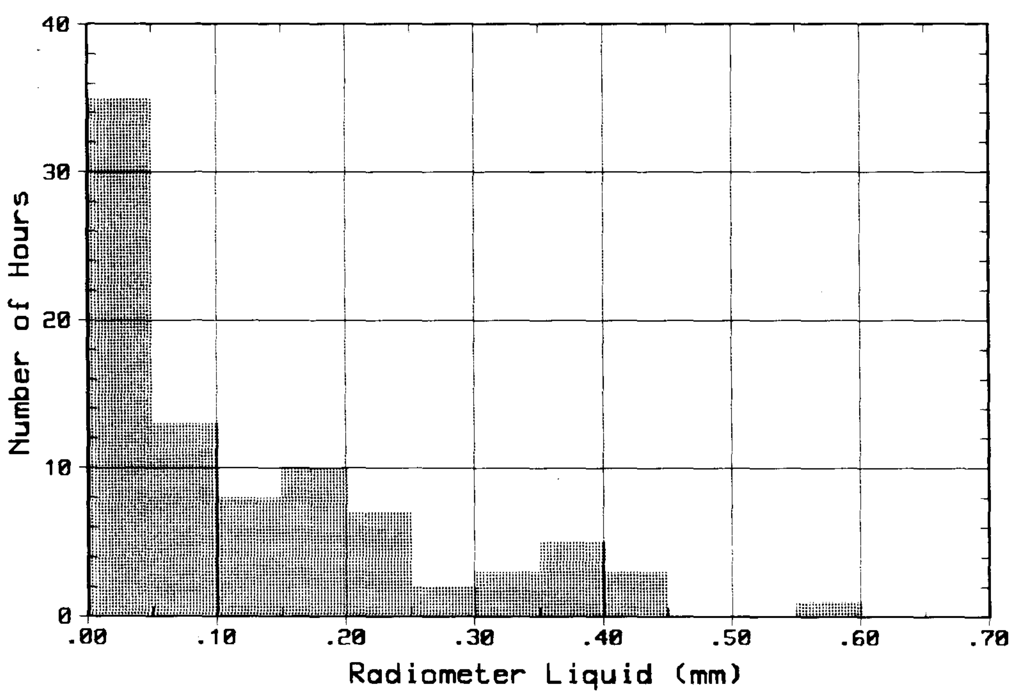


Figure 5-2. - Distribution of 87 hourly means of vertically integrated CLW amounts for SS and SC classes over Hannagan Meadow during early 1988.

potential of the low CLW periods can still be significant because of the high frequency of occurrence (Thompson and Super, 1987).

The distribution of the 33 hours with CLW from MC cases (not shown) had 82 percent of the hours with less than 0.1 mm and no hours exceeding 0.35 mm. Although convective clouds can have high instantaneous CLW contents, the wide spacing between active turrets and limited turret lifetimes presumably resulted in the low hourly mean values over the radiometer.

5.4.2 Diurnal Variations. - The diurnal distribution of CLW was examined by noting the frequency of occurrence of hourly mean CLW amounts (of at least 0.01 mm) for each of the 24 hours of the day, similar to figure 5-3. The range of was from 9 to 19 occurrences for particular hours over the course of the 1987 field effort, and from 2 to 7 for the 1988 cases. However, no pronounced diurnal variation existed during either field season; and all 404 hours from both seasons are combined in figure 5-3. All four storm classes are included in the figure. It is seen that the frequency of occurrence of CLW had a minimum near 1800 and a maximum near 1200. It is not apparent whether this variation is significant or simply the result of the random passage of synoptic scale weather disturbances. Additional observations would be needed to clarify this issue. At any rate, no pronounced afternoon maximum is obvious so solar heating was not a strong factor in the presence or absence of CLW.

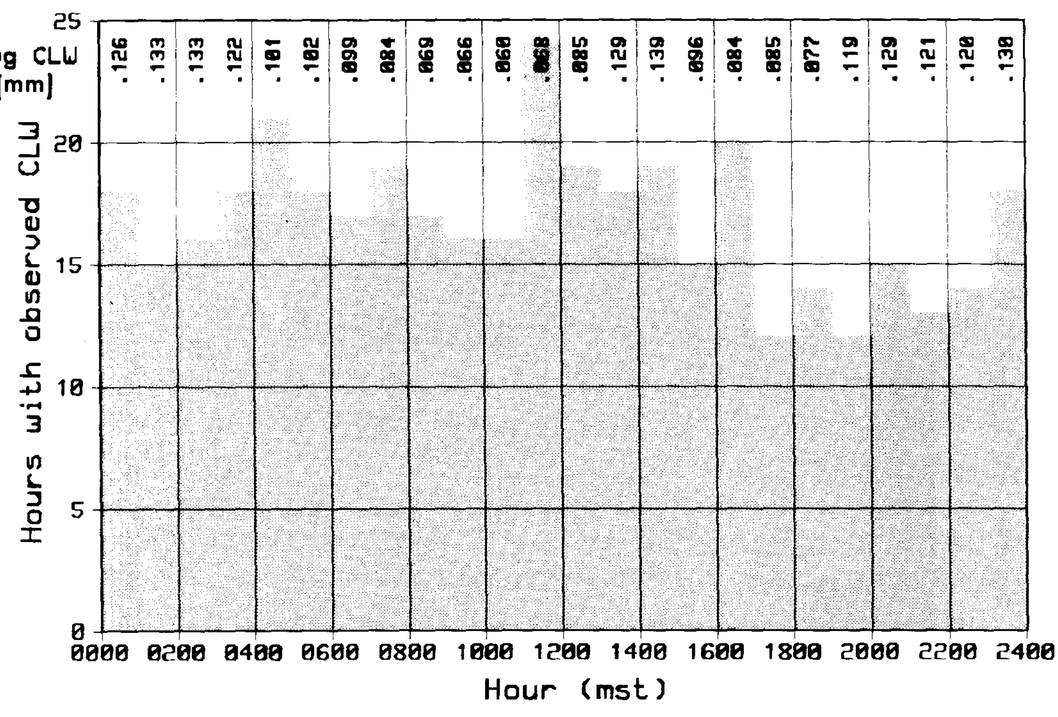


Figure 5-3. - Frequency of occurrence of CLW by time of day with mean amount noted for each hour. Data are for all storm classes for the combined 1987 and 1988 Arizona field seasons.

A plot similar to figure 5-3 for the limited MC cases (not shown) also gave no strong indication of a solar heating influence. However, many of the midday observations for these cases were disregarded because of the presence of rain. Therefore, it is suspected, but not demonstrated, that at least the MC cases had an afternoon maximum.

The mean CLW amount for each hour is listed on figure 5-3. There is a tendency for higher values during the nighttime hours. Values below 0.07 mm are confined to the 0800 to 1200 period while only 2 of 13 values above 0.10 mm exist outside the 1900 to 0600 time block. Again, further observations would be needed to test the reality of the suggested diurnal variation in mean CLW amount.

5.4.3 CLW Episodes. - A CLW (not storm) episode was defined, somewhat arbitrarily, by the near-continuous presence of CLW as indicated by the 1-hour mean radiometer data. Hours with suspected rain above the radiometer and/or a wet radiometer reflector were included in this analysis only so as not to arbitrarily truncate episodes. (Some of the 1988 episodes were truncated prematurely due to power outages.) Periods up to 2 hours without any detectable CLW were allowed to occur within an episode after it was observed that several lengthy CLW periods had a number of 1- or 2-hour gaps with no detectable water. A total of 41 episodes resulted with this definition, of which 29 occurred in 1987 and only 12 in 1988.

The cumulative distributions of the 41 CLW episodes, and hours with CLW present, are shown in figure 5-4 as functions of episode duration. It is seen that about one-half of the episodes were less than 7 hours duration. About a one-fourth (10) of the episodes lasted over 24 hours while another quarter lasted only 1 to 2 hours.

The cumulative distribution of hours with CLW reveals that half of all hours were associated with the 7 episodes of 30 hours or more duration. The 20 shortest episodes, of duration less than 7 hours, contributed less than 10 percent of all hours with CLW. Conversely, the 2 longest episodes (78 and 80 h) produced 25 percent of the CLW hours; and over half the CLW hours were associated with 6 of the 41 episodes. It is apparent that most of the CLW was produced by a limited number of storms that persisted for 1 to 3 days.

5.5 Relationships between CLW and Wind Direction

5.5.1 Happy Jack Wind Relations. - During early 1987, hourly mean wind directions were recorded at 30 m a.g.l. on a tower located atop a hill 70 m high near Happy Jack. These observations were not available until January 28 but were thereafter used to construct wind roses showing the frequency distribution of occurrence of detectable CLW, whatever its magnitude, versus wind direction. Tower winds were used rather than acoustic sounder winds to avoid the necessity of estimation with the latter which frequently had missing or suspect data at any particular level. Figure 5-5 shows such a wind rose for all 284 hours with mean values of CLW of 0.01 mm or more, excluding cases with rain above the radiometer. Clearly, most hours with CLW present were with southwest winds with 63 percent of all cases between 180 and 270 degrees true. A secondary maximum existed for northeast flow, with 20 percent of all cases having winds from 30 to 90 degrees. Both southwest and northeast flows were approximately perpendicular to the axis of the Mogollon Rim in the Happy Jack vicinity so both represent upslope flow. Such flow should force orographic lifting of the air and thereby enhance CLW production.

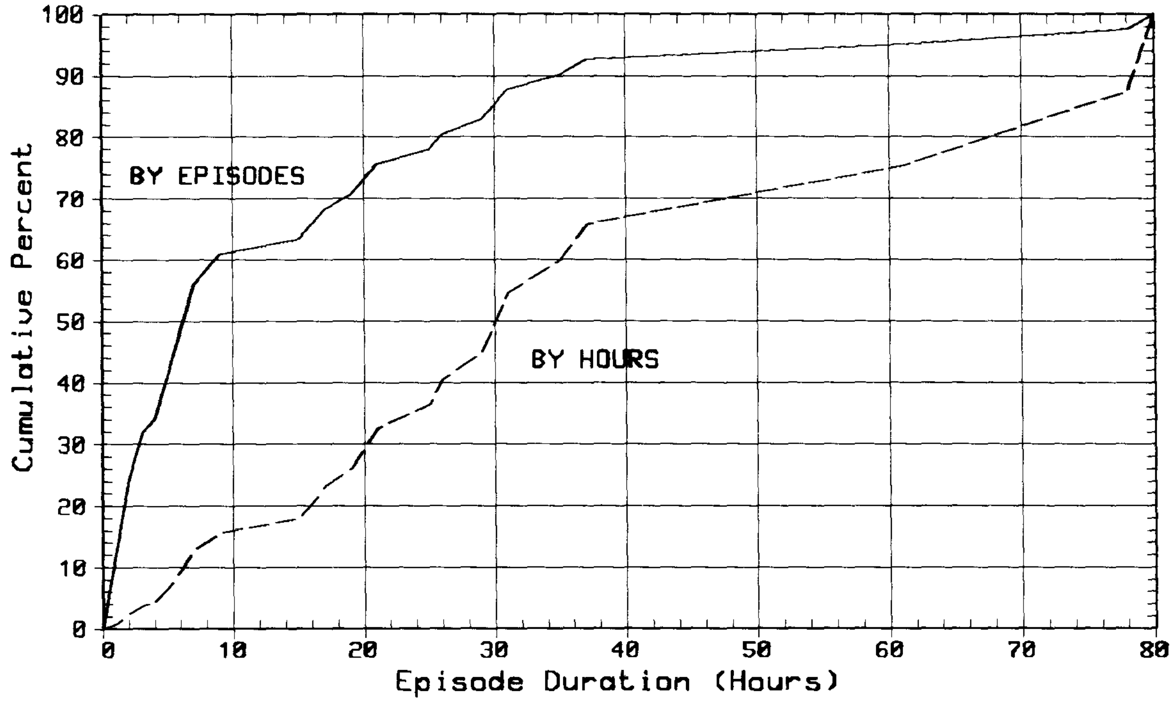


Figure 5-4. - Cumulative distributions of CLW episodes (solid line) and hours with CLW (dashed line) as functions of episode duration for the combined 1987 and 1988 Arizona field seasons.

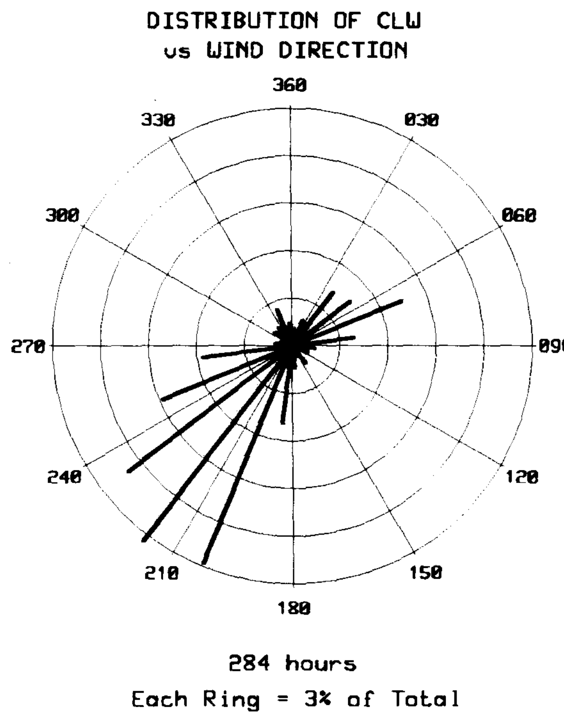


Figure 5-5. - Wind rose showing the distribution of hours with CLW versus wind direction (degrees true) for all storm classes over Happy Jack during early 1987.

A plot like figure 5-5 (not shown) was constructed using winds observed by rawinsondes released 42 km west-southwest of Happy Jack at Camp Verde. The figure showed a similar distribution for southwest flow, but only 8 percent of the CLW hours were associated with 700-mb winds from the 30- to 90-degree sector, far below the 20 percent shown for Happy Jack tower winds (fig. 5-5). This suggests the northeast upslope cases are primarily a low-level, local phenomenon over the Mogollon Rim, not usually observed near a 3 km altitude over the Verde Valley to the west. The 700-mb distribution showed a secondary maximum of 15 percent of all cases from 285 to 300 degrees, unlike the tower wind distribution.

It is interesting that figure 5-5 shows few westerly wind cases with CLW as such flow would also be upslope. Flow toward the small hill with the tower wind sensors was not blocked by higher nearby terrain for any direction although small hills of similar elevation exist about 0.5 km west and northwest of it. However, the general terrain slopes gently downslope for many kilometers for all directions clockwise from southeast to northwest. While local topographical features may have caused some distortion of the tower winds, the lack of westerly flow CLW cases appears to be due simply to the general rarity of west winds. The 700-mb wind directions were examined for all 99 rawinsondes tracked from Camp Verde. While 21 percent were between 240 to 300 degrees, only 3 percent were from 255 to 285 degrees. The distribution of all Happy Jack tower hourly mean winds, including nonstorm periods, showed a similar result. Further, when tower wind directions were partitioned by windspeed, it was found that stronger wind cases (> 5 m s^{-1}) were almost all between 195 and 240 degrees or 30 and 75 degrees; this suggests steering of the flow by the general terrain, with the low-level air forced upslope almost perpendicular to the long axis of the Mogollon Rim. Similar terrain-caused distortion of the free air flow was observed over the Grand Mesa, Colorado (Super et al., 1986). The lack of westerly flow at 700 mb over the Verde Valley may be partially due to general terrain steering by the Mogollon Rim, Black Hills to the west of the Mogollon Rim, and Verde Valley between these two barriers.

Plots similar to figure 5-5 were prepared for each of the four storm classes observed in 1987; that is, SS, SC, MS, and MC types. Since 173 hours were in the SS class, the plot for that type was similar to figure 5-5 but with a slightly lesser proportion of the hours with northeast flow and a slightly greater emphasis on southwest flow. The 55 hours of SC class were strongly concentrated with 60 percent of the cases from 210 to 255 degrees and 36 percent between 345 and 75 degrees. Almost all of the 33 hours classified as MC had a southerly component, with 70 percent of the cases between 135 and 225 degrees; 19 of the 23 hours of MS type (83 percent) were with upslope flow between 45 and 90 degrees. This type is the classic winter orographic cloud and might be expected with the occasional uplift of moist air from the northeast; it is a much more common cloud type in the central and northern Rocky Mountains of the United States where this cloud type usually occurs with westerly flow.

5.5.2 Hannagan Meadow Wind Relations. - Surface wind observations during the 1988 Hannagan Meadow field program were made about 7 m a.g.l. in the center of the large meadow since no higher ground was available. The distribution of wind direction for the 81 hours, with mean CLW measurements greater than 0.01 mm and valid wind data, is shown in figure 5-6. The predominant direction was westerly with 72 percent of the cases between 225 and 300 degrees. No CLW observations were made with winds between 300 and 90 degrees perhaps partially due to blockage by upwind terrain. A few CLW cases occurred with south-southeasterly flow. The westerly cases may have been aided by upslope motion along drainages in that general direction, but the irregular nature of the topography in the region makes it difficult to judge.

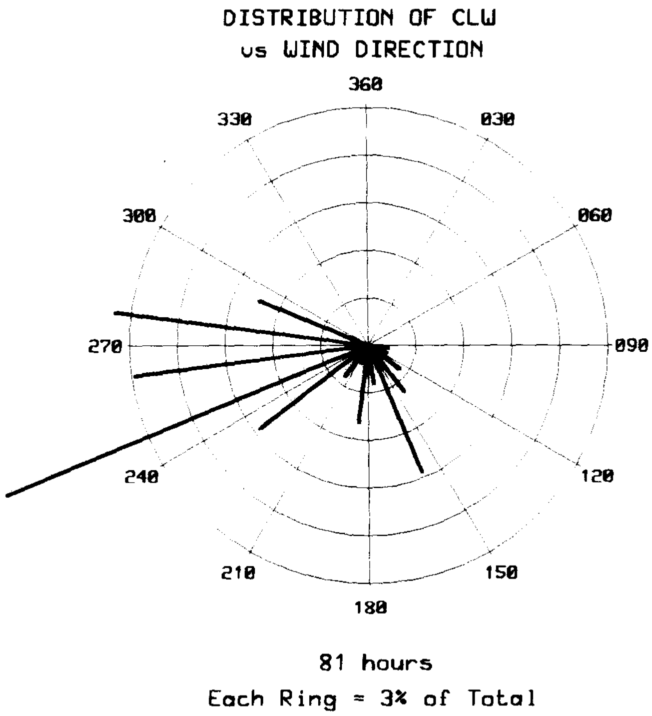


Figure 5-6. - Wind rose showing the distribution of hours with CLW versus wind direction (degrees true) for all storm classes over Hannagan Meadow during early 1988.

Similar wind roses (not shown) were produced for the 29 hours with SS classification and the 52 hours classified SC. The former had a wide range of directions from 90 to 300 degrees, with 38 percent between 240 and 300 degrees and 45 percent from 135 to 195 degrees. The SC hours were more consistent with 83 percent between 225 and 285 degrees.

5.6 CLW Flux Estimates

5.6.1 General Considerations. - The horizontal flux of CLW has been estimated for each hour of the storm episodes observed during the 1987 and 1988 winter field seasons. To convert measurements of integrated radiometer CLW to flux, it was necessary to make assumptions about both the vertical windspeed profile and the vertical distribution of the CLW.

A basic calculation of the volume flux (VFz) for any layer at mean height (z) having windspeed (Vz) and cross-sectional area (Az) can be given by:

$$VFz = Az \times Vz \tag{5-1}$$

(after Thompson and Super, 1987). The CLW flux (CFz) for each layer can then be calculated by:

$$CFz = VFz \times CLWz \tag{5-2}$$

where CLWz is the vertically integrated CLW for the layer. The total CLW flux is then the summation of the flux for all layers. Since 1 g of CLW is equivalent to 1 cm^3 liquid water (Fg), the flux in grams per second per meter crosswind is:

$$Fg = CLWz \times Vz \times 1{,}000 \qquad (5\text{-}3)$$

where CLWz is in mm, and Vz is in m s^{-1}.

Neither the vertical distribution of the windspeed nor that of CLW were routinely measured throughout the entire cloud layer. Therefore, it was necessary to make some assumptions about these distributions that were based on periodic observations taken throughout the 1987 field season. In the case of windspeed, the doppler acoustic sounder used in 1987 usually provided data in the lowest 570 m a.g.l. All available wind measurements were investigated and indicated the highest level observed by the acoustic sounder was often representative of the mean windspeed in the lowest 1 to 2 km as measured by aircraft and pibals. Therefore, available acoustic sounder data near 570 m a.g.l. were assumed to represent the lowest 2-km layer above Happy Jack with possible adjustment whenever aircraft winds were also observed in that layer.

All Happy Jack wind estimates above 2 km a.g.l. were based upon either (a) upwind rawinsondes from Camp Verde or Winslow (fig. 2-2), or (b) the preferred aircraft observations over the Happy Jack vicinity when available. These two measurement systems also provided estimates for the lowest 2 km when acoustic sounder data were unavailable. The previously noted wind study indicated that upwind rawinsonde winds were found to usually provide good to very good estimates of actual winds over Happy Jack as measured by the aircraft.

Knowledge of the vertical distribution of CLW was obtained primarily from aircraft sampling over Happy Jack as no aircraft sampling was done over Hannagan Meadow. For reasons of safety, the aircraft was not flown in cloud within 300 m of the highest terrain, which resulted in a minimum flight altitude of 2930 m m.s.l. Thus, the cloud layer in the lowest 640 m over Happy Jack could not be sampled. However, many clouds were sampled at and above the minimum altitude, providing information of the CLW distribution further aloft.

The general indication from several SS and SC storms was that the CLW tended to be concentrated in the lower positions of the clouds. (A similar distribution was found over the Grand Mesa, Colorado; see Holroyd and Super, 1984). For example, aircraft sampling of the Arizona synoptic scale storms generally revealed little CLW at altitudes above 5 km m.s.l. (2.7 km above Happy Jack). Also, CLW was sometimes detected by the radiometer in the lowest 640 m a.g.l. when the aircraft was observing exclusively ice crystal clouds at that altitude and above.

When viewed from a distance, the barrier was usually obscured in cloud and/or snow during storms at Happy Jack or Hannagan Meadow. This indicated that cloud base was generally below the crest elevation. However, cloud liquid was not often observed by the tower-mounted icing probes at the two sites; and visual observations there indicated cloud base was normally somewhat above treetop levels. It is thought that low-level mechanical mixing of the cloudy air resulted in loss of cloud droplets to the trees in most instances, thereby improving local visibility.

5.6.2 Happy Jack Flux Estimates. - The method by which the Happy Jack hourly horizontal CLW flux was estimated was as follows. In the event that cloud tops were generally less than 2 km above Happy Jack as observed by radar or aircraft, the CLW flux was calculated from equation (5-3) using the highest level (570 m a.g.l.) acoustic sounder speed measurement, or an estimate for that level based on lower level observations and/or other sensors in the absence of 570-m sounder data, and the total integrated CLW amount from the radiometer. If cloud depth consistently exceeded 2 km a.g.l., a second layer was added. In that case, 50 percent of the integrated CLW was assumed to be in the lowest kilometer (2290 to 3290 m m.s.l.); and the speed for that layer was again considered to be that measured (or estimated) at 570 m. The other 50 percent of the total CLW was assumed to lie above 1 km a.g.l. The thickness of this designated upper layer was variable, depending upon overall cloud tops.

The mean windspeed for the upper layer was estimated using aircraft observations when available or otherwise rawinsonde data. Winds further aloft than 4.9 km m.s.l. were never used because CLW was rarely detected that high. While this approach for calculating CLW flux was of necessity somewhat simplistic, it is believed the resulting estimates are reasonable because vertical gradients of windspeed and CLW were usually moderate.

For predominantly convective storms (MC), flux estimates were based on a single layer only using the highest level acoustic sounder wind. This technique was applied regardless of the cloud top height as vertical wind shears were generally limited and the convective cells moved as discrete entities at speeds approximating those recorded at 570 m above Happy Jack.

5.6.3 Hannagan Meadow Flux Estimates. - Calculation of horizontal CLW flux for 1988 storm episodes was done using the same general procedures as for the 1987 data set. However, differences in the available data set necessitated some modifications of the assumptions used in estimating the hourly average horizontal wind component. The primary differences were the lack of radar, local rawinsondes, and aircraft measurements. Unavailability of these data precluded reliable determination of cloud depths during storms. Thus, it was not possible to use a two-layer approach as was done with the 1987 data set for those storms having cloud depths consistently greater than 2 km. Instead, the conservative assumption was made that winds as measured by the (new) doppler acoustic sounder in the lowest 1 km were applicable to the entire cloud depth; this probably provided an underestimate of the flux for most cases.

Plots of the sounder hourly average winds were generated for each hour the radiometer liquid values equaled or exceeded 0.01 mm. These were inspected to estimate windspeed and direction values near 600 m a.g.l., or approximately the level used in the 1987 calculations. The sounder system was programmed to provide measures of data quality in each height bin (30-m intervals). Frequently, data were of marginal quality at or above the 600-m level; a judgment had to be made concerning representative wind values. It was noted that often windspeeds rose with altitude in the lower bins (as would be expected), but then dropped sharply prior to reaching the 600-m level as the data quality began to degrade. Usually, wind directions also shifted markedly at this point, most commonly backing with height. The profiles produced were suggestive of a low-level jet, but the high frequency of occurrence gave grounds for suspicion concerning this interpretation. As a check, the sounder- and pibal-produced wind profiles were compared for the 41 pibals tracked during the 1988 season. Results indicated that areas of pronounced speed reductions coupled with backing winds and degradations in data quality (from "good" to "satisfactory", for example) on the sounder data were most often false. The pibal profiles showed that the windspeed over Hannagan Meadow generally either tended to increase with height or remained at a relatively constant value after reaching that value near the ground. Thus, the sounder data at the level desired were often inaccurate. The procedure finally used was to look at all available data for each hour, including Tucson and Winslow rawinsonde and Hannagan Meadow pibal data closest in time, and make a judgment on a representative speed. Based on the pibal comparisons, the maximum sounder produced hourly average windspeed in the layer from the surface to 600 m was generally taken to represent the CLW transport speed for that hour; this is believed to be a conservative approach.

5.7 Distributions of CLW Flux

5.7.1 CLW Flux Estimates by Storm. - Horizontal CLW flux estimates are tabulated in table 5-2 for 11 storm episodes in 1987 with valid data and 2 with some questionable data due to rain; 3 episodes classified as MC were not included in the table because of doubtful seedability (see sec. 8). In addition, estimates are given for 14 episodes in 1988 although some have incomplete radiometer data. Over Happy Jack, the total flux per storm episode ranged from about 0.1 to 42 x 10^7 g per meter of crosswind distance. The hourly flux averaged over the duration of each storm ranged from 10 to 2710 g s^{-1} per meter of crosswind distance. The total storm flux over Hannagan Meadow was as large as 29 x 10^7 g for one episode and as small as 0 in two cases. The average hourly flux per storm ranged from 0 to 1525 g s^{-1}.

The character of the episodes in table 5-2 varied greatly, from lengthy periods having significant CLW almost without interruption to episodes with many hours of precipitation but little or no CLW. The four episodes with the highest total CLW fluxes also had precipitation during most of their durations as measured by the high-resolution gauges at Happy Jack and Hannagan Meadow, respectively.

Table 5-2 also shows that 75 percent of the total CLW flux for the 1987 field season (ignoring the two episodes with questionable values and the MC cases) occurred during only three storm periods that lasted a total of 156 hours. Conversely, 6 of the 11 episodes with the lowest CLW estimates had a total of 167 hours duration but contributed only 13 percent of the total flux. Those three episodes that produced three-quarters of the total flux had CLW maxima associated with cold front passages--either pre- or postfrontal, or both. Secondary maxima sometimes were observed to be related to passage of a surface low or trough aloft. Details of the evolution of each storm are discussed in the appendix. The important point is that relatively few long-duration storm episodes contained much of the seeding potential for a winter season.

This point received further emphasis during the next winter's field effort. The total flux for the 1988 field program was approximately one-third that of the previous season. While the observations were made at different locations on the Mogollon Rim and some 1988 data are missing, the primary cause for this difference is believed to be less-frequent large-scale storminess during the latter winter. The single major storm of February 1-3, 1988, produced two-thirds of the total estimated flux for the field season. In studies of Colorado mountain precipitation, the presence or absence of a few large winter storms has resulted in either heavy or light seasonal snowpacks. It is therefore not surprising that a few large storms could drastically affect the amount of CLW flux available during a winter over the Mogollon Rim.

Table 5-2. - Summary of CLW flux estimates ranked by total flux per storm episode.

Date	Total flux* (x 10^7 g)	Rank	Mean flux* (g s^{-1})	Episode duration (h)	Percent hours with CLW	Percent hours with precipitation	Cumulative total flux* (x 10^7 g)	(%)
2-23 to 2-26-87	41.9	1	1455	80	73	69	41.9	35
1-30 to 1-31-87	24.4	2	2710	26	96	85	66.3	56
3-15 to 3-17-87	23.5	3	1305	50	96	78	89.8	75
2-13 to 2-14-87	9.2	4	1155	22	86	41	99.0	83
2-19 to 2-21-87	5.3	5	305	48	58	46	104.3	87
2-4-87	3.9	6	670	16	94	31	108.2	91
1-15 to 1-17-87	3.4	7	150	64	33	59	111.6	93
1-28-87	3.1	8	1730	5	100	0	114.7	96
2-17 to 2-18-87	2.8	9	255	31	71	13	117.5	98
2-15 to 2-16-87	1.8	10	200	25	60	0	119.3	100-
1-19 to 1-20-87	0.1	11	10	26	12	69	119.4	100
The following fluxes were overestimated by unknown amounts due to rain above the radiometer:								
3-8 to 3-9-87	13.1	—	1215	30	90	67	—	—
3-6 to 3-7-87	3.7	—	535	19	79	37	—	—
Hannagan Meadow observations:								
2-1 to 2-3-88	29.1	1	1525	53	74	91	29.1	67
1-17 to 1-19-88**	6.4	2	?	52	?	96	35.5	82
1-16 to 1-17-88	2.5	3	330	21	67	86	38.0	88
2-26 to 2-27-88	2.4	4	415	16	69	56	40.4	94
2-25 to 2-26-88	1.0	5	345	8	75	100	41.4	96
2-27-88	0.6	6	240	7	71	0	42.0	97
3-3-88	0.5	7	115	12	50	67	42.5	98
3-2-88	0.3	8	75	11	64	27	42.8	99
2-17-88**	0.3	9	?	11	?	73	43.1	100-
1-30-88	0.1	10	95	3	100	0	43.2	100
1-21 to 1-22-88	0.0	—	0	3	0	100	43.2	100
2-18 to 2-19-88	0.0	—	0	12	0	75	43.2	100
The following episodes are included for completeness although little or no radiometer data were obtained:								
2-4 to 2-5-88**	?	—	?	17	?	100	—	—
3-7 to 3-8-88**	?	—	?	13	?	100	—	—

* Per meter crosswind distance.
** Episodes with significant missing radiometer data.

The largest flux-producing storm, with 35 percent of the 1987 total, occurred on February 23-26. This storm also produced considerable snowfall over a wide area. For example, the Prescott airport was closed for a few days due to about 0.5 m of snow on the runways and insufficient equipment for removal. Sections of Arizona interstate highways were closed for extended periods. The storm, locally reported as producing the heaviest snowfall in 20 years, resulted in a total snow water equivalent of 80 mm at Happy Jack. It is questionable whether any cloud seeding would be desired or allowed during such a storm. However, the other three storms that produced more than 20 x 10^7 g of CLW flux were much less disruptive, with snow water equivalent amounts between 20 to 46 mm falling near the radiometer. Table 5-2 shows that the major flux-producing episodes lasted for one to a few days and naturally snowed for the majority of that time. Accordingly, the needs of society for increased water will have to be carefully balanced against possible or perceived temporary inconveniences during any future cloud seeding program in Arizona.

5.7.2 CLW Flux Compared with Precipitation. - CLW flux values are placed in better perspective by converting to precipitation rates, which are easier to comprehend. This also helps address the probable upper limits of precipitation that seeding might produce in a short time frame. The hourly flux distribution during the two field seasons is given in table 5-3; each range is twice the width of the previous one. Table 5-3 shows that the large majority of hours with observable CLW had fluxes below 10^7 g. The highest hourly mean value measured during almost 4 months of sampling was 5.2 x 10^7 g. Since it is difficult to relate to grams of liquid water passing overhead, table 5-4 was constructed using the midpoint of each range of table 5-3, converted to precipitation rate over three different distances by assuming that all the CLW flux became snow that fell uniformly over each noted downwind distance. The melted water equivalent of the snowfall is given in millimeters per hour. To interpret instead in terms of snow depth per hour, the values in table 5-4 should be multiplied by roughly a factor of 10. The downwind distances were chosen to bracket the minimum and maximum ranges over which snow caused by ground-based seeding would likely fall for the large majority of ice crystal growth rates and settling velocities and typical ranges of wind velocities experienced over western mountain ranges. Snowfall from airborne seeding would probably spread over somewhat larger distances. The values of table 5-4 represent the maximum precipitation rates physically possible for the stated assumptions as they represent conversion of all the CLW flux to snowfall.

Table 5-3. - Distribution of all hourly CLW flux amounts by field season.

Hourly flux (grams x 10^6 per meter crosswind)	Number of hours in noted range (1987)	(1988)
0.1 to 1.0	114	25
1.1 to 3.0	112	22
3.1 to 7.0	83	16
7.1 to 15.0	43	17
15.1 to 31.0	12	7
31.1 to 63.0	5	0
Totals	369	87

Table 5-4. - Precipitation rates (mm h^{-1}) corresponding to indicated CLW fluxes if uniformly deposited over three different distances.

Hourly flux (grams x 10^6 per meter crosswind)	Downwind distance 3 km	10 km	30 km
0.5	0.2	0.05	0.02
2.0	0.7	0.2	0.1
5.0	1.7	0.5	0.2
11.0	3.7	1.1	0.4
23.0	7.7	2.3	0.8
47.0	15.7	4.7	1.6

It is apparent that the maximum possible precipitation rates are limited for all but a small fraction of hours by the availability of CLW flowing over the barriers. This is not surprising when considering the distribution of natural precipitation rates during winter on the Mogollon Rim. The median rate using a large orifice gauge at Happy Jack (0.05-mm resolution) was 0.36 mm h^{-1} and the mean was 0.86 mm h^{-1} for 257 hours of measurements. The maximum precipitation observed in 1 hour was 6.05 mm. Similar values were found at Hannagan Meadow with a median of 0.31, a mean of 0.72, and a maximum of 8.43 mm h^{-1}, all based on 190 hours of measurements with a similar gauge. These values are in reasonable agreement with those given in table 5-4 as they should be since the precipitation is derived from CLW. An important point from this discussion is that natural precipitation over the Mogollon Rim infrequently exceeded a few millimeters per hour because it is limited by the supply of condensate; that is, the CLW production. Cloud seeding has the same limitation and cannot result in heavier snowfall rates than already occur in nature. When nature is very efficient in converting CLW into snowfall, no significant excess is available so seeding will not markedly increase the precipitation rate. When nature is inefficient, the seeding may result in a significant increase in precipitation; but hourly rates should not be greater than during naturally efficient periods.

5.7.3 CLW Flux Versus Storm Type. - Table 5-5 shows the variation of CLW flux with storm period classification and shows that the bulk of the 1987 flux contribution was from the SS hours because of their high frequency. Moreover, the hourly flux tended to be higher during the SS and SC hours than during the MC and MS hours, which overall made minor contributions. Hours classified as SC were most important at Hannagan Meadow in 1988 both in terms of frequency of occurrence and total flux production. The synoptic scale events were clearly the important CLW flux producers during both field seasons whether convection was predominant or not. Mesoscale systems were infrequent and had lower mean hourly flux values. As a consequence, mesoscale systems produced little of the seasonal flux.

Table 5-5. - CLW flux per meter crosswind by storm classification.

Storm classification	SS	SC	MS	MC	Totals
1987					
Total flux x 10^7 (g)	99.7	17.3	3.4	5.1	125.5
Hours of observation	184	59	22	33	298
Mean flux x 10^6 (g h^{-1})	5.4	2.9	1.5	1.5	—
1988					
Total flux x 10^7 (g)	10.9	32.3	0.0	0.0	43.2
Hours of observation	32	55	0	0	87
Mean flux x 10^6 (g h^{-1})	3.4	5.9	0	0	—

5.7.4 CLW Flux Versus CLW Amount. - Figure 5-7 shows the distribution of the 1987 CLW flux plotted against mean amounts of vertically integrated CLW for all hours with at least 0.01 mm. The low values of CLW contributed much of the seasonal flux as previously found over the Grand Mesa, Colorado (Boe and

Super, 1986) because of the much higher frequency of occurrence of CLW amounts less than 0.15 mm (fig. 5-1). About 45 percent of the total flux was due to 83 percent of all hours that had mean CLW amounts of 0.15 mm or less. Conversely, 5 percent of all hours that had CLW amounts in excess of 0.35 mm yielded almost 30 percent of the total flux.

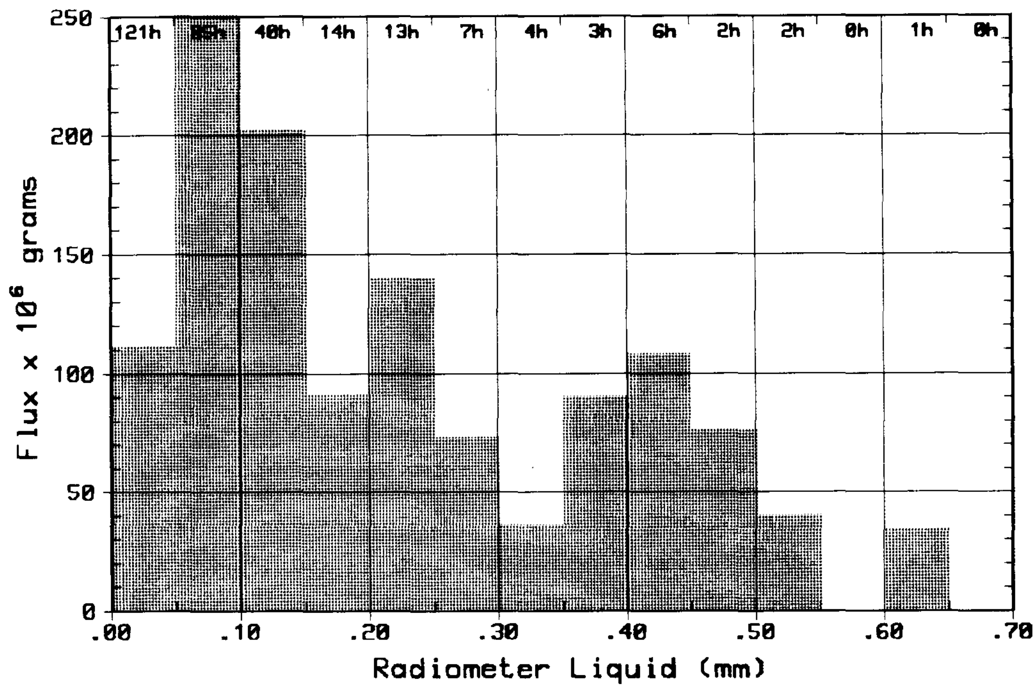


Figure 5-7. - Distribution of CLW flux per meter crosswind versus vertically integrated CLW amounts with the number of hours within each range noted; data are for all storm classes over Happy Jack during early 1987.

A similar plot for the more limited 1988 observations is given by figure 5-8, which shows only 27 percent of the total flux from hours with 0.15 mm or less CLW. A total of 10 SC hours with CLW amounts of 0.30 mm or more were chiefly responsible for the greater importance of the wetter periods, and all occurred over a several-hour period on February 2-3. It is possible that a distribution similar to figure 5-7 would have resulted if a few more large-scale storms passed Hannagan Meadow in early 1988.

Examination of the entire 385 hours with CLW flux estimates from both field seasons has shown that about half of the total CLW flux occurred during 15 percent of the time that the radiometer observed values greater than 0.20 mm. Conversely, 41 percent of the hours had radiometer values from 0.01 to 0.05 mm and less than 9 percent of the total flux. Similar highly skewed distributions are common for mountain precipitation (see sec. 6.4 or Super et al., 1986), which is derived from CLW flux.

It might appear attractive to concentrate seeding during the wetter (high CLW) periods in anticipation of high snowfall yields. However, the periods with low CLW amounts should not be discounted without further investigation. While the seeding potential of these periods may be low in terms of hourly snowfall rates, the

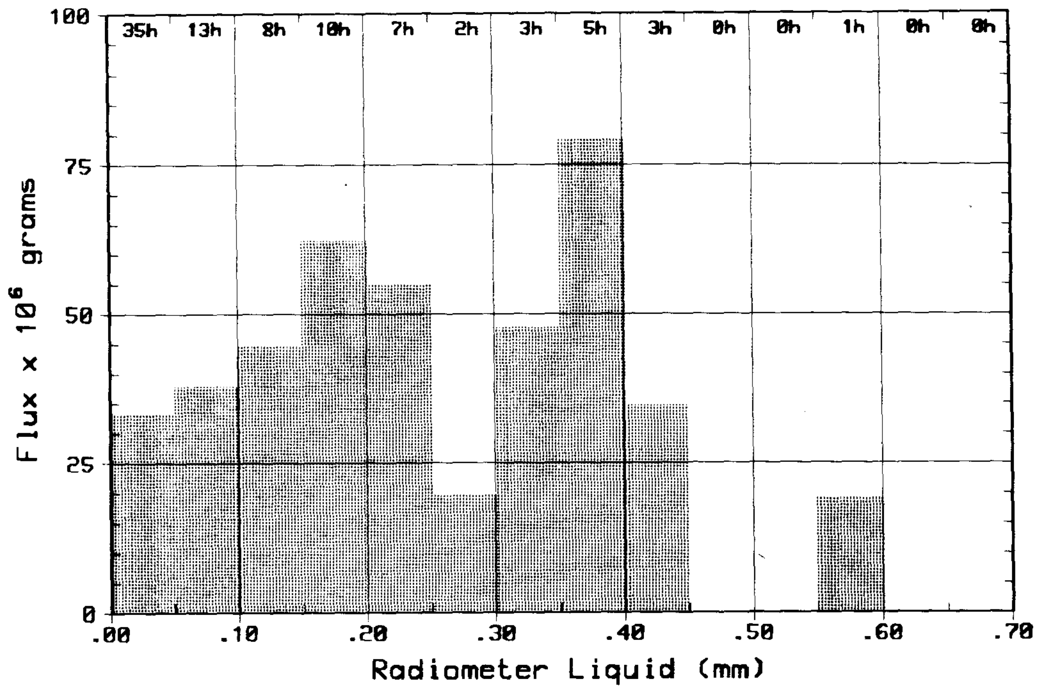


Figure 5-8. - Distribution of CLW flux per meter crosswind versus vertically integrated CLW amounts with the number of hours within each range noted; data are for all storm classes over Hannagan Meadow during early 1988.

seasonal contribution may be significant due to the higher frequency of opportunities. Ideally, both wetter and drier CLW periods should be seeded if further study indicates both have the potential for snowfall enhancement that is socially acceptable.

5.7.5 CLW Flux Versus Wind Direction. - The 277 hours with both valid CLW observations and Happy Jack tower wind data were used to partition the 1987 CLW flux by wind direction. The distribution in figure 5-9 indicates that 375 million grams, or 30 percent of the total flux, occurred with south-southwesterly winds (195 to 210 degrees); 55 percent of the total flux was associated with wind directions from 195 to 240 degrees (i.e., generally southwesterly flow), and 70 percent was associated with winds between south and west. The entire 0- to 90-degree quadrant contributed 16 percent of the total flux while the 270- to 360-degree quadrant yielded 13 percent of the total. Flux from the southeast was negligible.
The 81 hours from 1988 with both CLW and wind data were also examined. Three-quarters of the total flux occurred with winds between 225 and 270 degrees; that is, between southwesterly and westerly. The only other important direction was between south-southeast and south with 13 percent of the flux.

5.7.6 Ground-Based Seeding Considerations. - The strong tendency for CLW flux to be associated with southwesterly or westerly flow could make ground-based seeding very attractive since generators need to be located only for a limited range of wind directions. This assumes that ground-based seeding would result in adequate vertical and horizontal spreading of the AgI (silver iodide) seeding material, and those temperatures of the seeded portion of the cloud would frequently be cold enough for AgI ice crystal nucleation. Section 9 addresses these issues and indicates that a seeding plume would often reach 700 m a.g.l. before passing the Mogollon Rim crest. With typical temperature lapse rates during storms, the plume

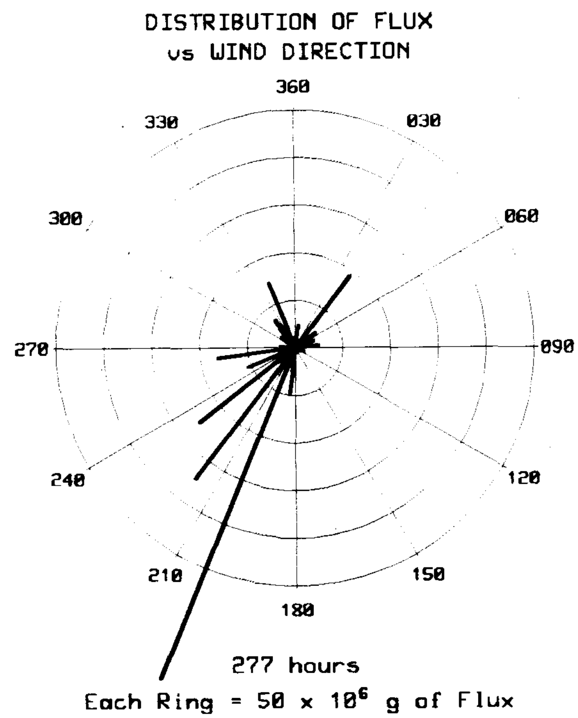


Figure 5-9. - Wind rose showing the distribution of CLW flux per meter crosswind versus wind direction (degrees true) for all storm classes over Happy Jack during early 1987.

top should then be at least 4 °C colder than the surface. With this in mind, the Happy Jack surface temperature was examined for all 1987 SS, SC, and MS hours with CLW flux and winds between south and west (the limited number of MC cases were excluded for reasons discussed in sec. 8). No significant relationship was found between temperature and the flux magnitude, and surface temperatures ranged from -7 to +8 °C though most hours were colder than 0 °C. Assuming that a seeding plume top would be typically 4 °C colder than the surface and that the top temperature must be colder than -6 °C for significant ice crystal formation even with exotic types of AgI, a surface temperature less than -2 °C would be required for ground-based seeding to have any promise. This condition was satisfied at Happy Jack during 59 percent of the hours with CLW flux from the most common wind directions. However, if plume tops colder than -9 °C are required as probable for conventional types of AgI, then only 20 percent of the hours qualified and these were from just two storm periods.

The 1988 CLW flux and temperature data were also examined for the 78 hours that had both observations available. Measurements were used for all wind directions since almost all were between 150 and 270 degrees. Most hours were colder than freezing at the surface when CLW was detected above the radiometer, and only 12 percent were warmer than 2 °C. Again, assuming the top of a ground-released AgI plume would be 4 °C colder than the surface (in this case the Hannagan Meadow site), plume tops would have been -6 °C or colder for 33 percent of the hours. The more stringent requirement of plume tops colder than -9 °C would have been satisfied on only 6 of the 78 hours (8 percent). These results, while based on more limited data, are less encouraging than those from Happy Jack even though Hannagan Meadow is about 450 m higher than Happy Jack. The Hannagan Meadow location is also further south than Happy Jack, but the primary cause of the results shown is likely just winter to winter variations in the weather. As discussed in section 2.3, there are indications that early 1988 was warmer and drier than normal.

The results just discussed suggest that ground-based AgI seeding may be possible during some storms over the Mogollon Rim, especially if types of AgI are used which are able to nucleate ice at warm temperatures. However, many storms will likely be untreatable by this method even though section 9 is encouraging about the vertical and horizontal dispersion of ground-released plumes. It is possible that storms with embedded convection would significantly enhance vertical mixing of the seeding material to higher, colder levels than indicated by the experiments of section 9. Further investigation of this possibility is warranted.

The lower (and usually wetter) portions of the clouds that can be reached by ground seeding are generally too warm for ice nucleations by AgI according to test results from cloud simulation laboratories. However, it will be important to measure the temperature at which significant ice crystal nucleation can be achieved in actual Arizona clouds in case the laboratory test chambers fail to accurately simulate such clouds.

Ground-based seeding with a conventional type of AgI appeared to be inefficient in about half the storms in Montana, much further north, because of warm temperatures in the lower cloud regions (Super and Heimbach, 1983). Thus, these results from Arizona, indicating that the same type of AgI would probably produce significant ice crystals in a much smaller fraction of the storms, should not be too surprising.

5.7.7 CLW Flux Versus Streamflow. - It is of interest to compare the CLW flux values with streamflow from the same areas. The region immediately north of Happy Jack is drained to the southwest by Dry Beaver and Wet Beaver Creeks, which join the Verde River near McGuireville to form a combined drainage of 655 km^2. This area's mean annual runoff for the period 1966 to 1982 was 63,471 acre-ft (78.3×10^6 m^3). The crosswind extend of these watersheds for southwest flow was about 31 km near the 2.1-km m.s.l. altitude contour. With a CLW flux of about 125×10^7 g per meter of crosswind, a total flux of approximately 39×10^{12} g resulted. Because 1 acre-ft is equivalent to 1.23×10^9 cm^3 (or g) of water, the 2-month flux across these drainages was near 32,000 acre-ft (39.5×10^6 m^3), or half the mean annual runoff from the same drainages.

For the early 1988 period, it is appropriate to use the streamflow of the Black River measured near Maverick, which is a drainage of 816 km^2 and includes Hannagan Meadow. The mean annual runoff for the period cited above was 90,109 acre-ft (111.2×10^6 m^3), and the crosswind extent of the watershed was about 37 km for west-southwesterly flow. The early 1988 CLW flux over Hannagan Meadow was estimated at about 43×10^7 g. Assuming that Hannagan Meadow was representative of the entire crestline of the watershed, the CLW flux was equivalent to 13,000 acre-ft (16.0×10^6 m^3) of water or 16×10^{12} g; this is over 14 percent of the average annual runoff. However, the degree to which Hannagan Meadow is representative of the entire basin crestline is uncertain because, unlike the rather uniform terrain of the Happy Jack region, the headwaters of the Black River have irregular topography. Radiometer data are also missing for all or portions of several 1988 storms due to electrical power outages and computer problems.

A significantly longer period of record would be required to test the representativeness of the early 1987 and 1988 observations for typical Arizona winters. Further, determining what portion of the CLW flux can be converted to snowfall is a different and complex subject. However, it is very encouraging that a significant CLW flux was observed in the initial Arizona field programs, each less than 2 months duration. If similar amounts of CLW pass over the Mogollon Rim throughout typical winters, the required "raw material" for cloud seeding is present in reasonable abundance.

5.7.8 CLW Flux Comparisons with Other Locations. - It is of interest to compare the findings of section 5.7 with the results of other studies although few estimates of CLW flux have been published. Some CLW flux estimates have been reported from investigations in the Tushar Mountains of southern Utah, a generally north-south oriented barrier about 430 km north-northwest of Happy Jack. Rauber and Grant (1987) estimated the amount of CLW passing the crest for a single storm in February 1983. This was done with rawinsonde wind data for the elevation of the barrier crest and scanning microwave radiometer measurements collected about 20 km west of the crest at a much lower elevation. It was necessary to normalize the radiometer data to the zenith so the observations may not totally represent conditions over the crestline. The resulting estimate of total CLW flux for a 13-hour period was 12.5 x 10^7 g per meter of ridgeline, equivalent to approximately 13 percent of the mean annual runoff from the area. Four storms in table 5-2 had more total CLW flux and were all of longer duration. Presumably, the Utah storm was chosen as a case study because it appeared to have substantial seeding potential. The Utah storm's flux estimate is similar to the wetter Arizona storms.

Rogers et al. (1986) reported on early 1985 data from the Tushar Mountains, also based on microwave radiometer and rawinsonde windspeed measurements. During this season, the radiometer was at a higher elevation than during 1983, located only about 5 km west of the barrier crest. The radiometer was operated in a combination of zenith-pointing and scanning modes so the latter had to be normalized to the zenith. Data were available from 135 "storm" hours from early February to mid-March 1985. During that period, it was estimated that about 1.6 x 10^{13} g (13,018 acre-ft) of CLW passed over the 50-km length of the barrier, which represents 34 percent of the mean annual runoff for the area. In order to compare with the 2-month totals of table 5-2, the 1.5-month total for the Tushar Mountains was extrapolated to 2.0 months and the flux was expressed per meter of crestline distance, which yields a value or 43 x 10^7 g. This is essentially the same as the early 1988 seasonal total of 43.2 x 10^7 g at Hannagan Meadow and about one-third of the early 1987 seasonal total of 119.4 x 10^7 g at Happy Jack. The 1985 Utah program was characterized by relatively dry weather types associated with more northerly flow than usual; thus the agreement with the dry 1988 observing period in Arizona should not be too surprising.

Rogers et al. (1986) also noted that nearly half of the early 1985 CLW flux passed over the barrier during a single 31-hour storm event. Almost 80 percent of the seasonal flux was due to only 3 of the 14 "storm" episodes. Similar distributions can be seen in table 5-2.

Thompson and Super (1987) presented the distribution of hourly CLW flux estimates from radiometer and wind observations on the Grand Mesa, Colorado, during January through March 1985. The distribution was approximately log-normal, with 10 percent of all hours with detectable CLW less than 40 g s^{-1} (per meter of crosswind distance) and 10 percent of all hours greater than 2150 g s^{-1}. The median value was 295 g s^{-1}. These values are in general agreement with those found in table 5-2. Aircraft observations of cloud water flux were also presented by Thompson and Super that were in good agreement with radiometer-derived values.

In summary, the limited available comparisons of CLW flux suggest that storm conditions are not radically different among the high elevation observing sites of Arizona, Colorado, and Utah. Hourly CLW flux estimates appear to be in reasonable agreement at the Arizona and Colorado sites, suggesting similar cloud liquid water contents. Storm and seasonal total CLW flux amounts appear similar between the Arizona and Utah sites. However, it would be expected that the mean frequency of CLW events would vary among the sites, with higher frequencies generally associated with higher elevations and higher latitudes.

5.8 Prediction of CLW

5.8.1 Observations Used. - It would be very useful for future cloud seeding programs to have a means of predicting when CLW would occur and in what amount. Toward this end, the more comprehensive data base collected in 1987 was used to determine which weather conditions, if any, could be linked to CLW production. All available hourly measurements were utilized in this attempt to develop a prediction scheme for CLW. The many observations are listed below:

a. From Happy Jack:

(1) Precipitation rate
(2) Temperature
(3) Dewpoint temperature
(4) Atmospheric pressure
(5) Pressure change (1 and 6 hours)
(6) Wind direction recorded at Happy Jack tower

b. From the Camp Verde rawinsondes:

(1) Wind component normal to the Mogollon Rim at the 700-mb level
(2) Temperature (700 and 850 mb)
(3) Dewpoint temperature (700 and 850 mb)
(4) Temperature-dewpoint depression (700 and 850 mb)
(5) Windspeed (700 and 850 mb)
(6) Wind direction (700 and 850 mb)
(7) Precipitable water
  (a) Total
  (b) Surface to 750 mb
  (c) Surface to 700 mb
  (d) Surface to 650 mb
  (e) 750- to 650-mb layer

c. From the Happy Jack radar:

(1) Cloud top heights
(2) Estimated cloud top temperatures (based on Camp Verde rawinsonde temperature profiles)

5.8.2 Correlations with CLW Amount. - From the many parameters listed above, the best relationship was found between the amount of CLW and 700-mb dewpoint temperature depression with a linear correlation coefficient (r) of -0.42 where the negative sign means an inverse correlation. Other relatively high associations were between CLW and the 700-mb dewpoint temperature ($r = 0.35$), Happy Jack surface pressure ($r = -0.31$), and Happy Jack dewpoint temperature ($r = 0.31$). No single parameter explained more than 18 percent of the variance in CLW amount. This is not surprising, for more than one condition has to be satisfied before CLW is produced. For example, having a moist air mass is a necessary but not sufficient condition; a source of vertical lifting must be present as well. Often CLW is diminished by precipitation as it is produced, further complicating any relationship between CLW and other parameters.

Many of the parameters were apparently unrelated to CLW amount; for example, surface pressure changes, 850-mb windspeed, and radar cloud tops. This last example is unexpected because it might be anticipated that high, cold cloud tops would result in greater ice particle production and thereby more CLW depletion.

Some parameters were poorly correlated with CLW but had other interesting relationships. For example, the 700-mb temperature was never colder than -12 °C or warmer than +1 °C when CLW was observed by the radiometer.

5.8.3 SLIP Index. - To predict the presence of CLW (as observed with the radiometer), an index was developed. This index, termed the SLIP (supercooled liquid production) index, is defined as:

$$\text{SLIP Index} = P + M - W \qquad (5\text{-}4)$$

The pressure term P is:

$$P = -5 \times (p - 778) \qquad (5\text{-}5)$$

where the pressure (p) is in millibars. The moisture term (M) is defined as:

$$M = 80 \times [5 - (T - DP)] \qquad (5\text{-}6)$$

where T and DP are the 700-mb temperature and dewpoint temperature in °C, respectively. The final term W (windows) is applied only when other select variables were observed outside ranges known to be associated with CLW production at the Happy Jack site. These parameters and their ranges are shown in table 5-6.

Table 5-6. - Window parameters for the calculation of the SLIP index.

Parameter	Lower limit	Upper limit
700-mb dewpoint	-14.0 °C	—
Surface pressure	—	774 mb
Surface temperature	-7.5 °C	—

If the mean hourly value for any given parameter was beyond the accepted limits, the SLIP index was set to zero.

The final criterion for the SLIP index is that it cannot be negative; if the index otherwise would be, it is set to zero. Attempts to include other constraints in the index such as the aforementioned dependence on wind direction, proved only to complicate matters. A plot of CLW production as a function of the SLIP index was developed for all hours with available data whatever the radiometer values, except for MC storm periods which were excluded. Data were estimated for the 700-mb level for 2 hours before and after the time of each rawinsonde release, which yielded 390 hours of data. A correlation coefficient of 0.54 resulted between the amount of CLW measured and the SLIP index, which explains only 29 percent of the variance. The SLIP index does well in predicting the presence of CLW, but is less able to predict the quantity. This shortcoming is likely partially due to the lack of measurements of low-magnitude but sustained vertical velocities, which are believed to be significant in the production of CLW. The pressure term in part may compensate for this deficiency as the major periods of positive vertical velocities were thought to have been associated with the cyclonic storms (and hence lower surface pressures), which were the largest CLW producers.

The overall effectiveness of the SLIP index as an indicator of the presence of CLW is evaluated with the aid of table 5-7. Of the 390 hours of data in table 5-7, only 12 had detectable CLW (hourly mean of at least 0.01 mm) when the SLIP index was zero; and none of these 12 hours exceeded 0.02 mm. Only 10 percent of the hours with an index less than 150 had detectable CLW, and only 12 percent of the hours in this low range occurred during designated storm episodes.

Table 5-7. - Effectiveness of the SLIP index for low, moderate, and high ranges of probable CLW existence.

Range of SLIP index	Total number of hours	Percent hours with CLW $\geq$ 0.01 mm	Mean CLW (mm)	Percent hours in storm episode*
0 to 149	216	10	.005	12
150 to 249	37	54	.035	60
250 and up	137	85	.086	97

* Hours classified as SS, SC, or MS.

Eighty-five percent of the hours with a SLIP index of 250 or greater had detectable CLW, and 97 percent of these hours were during storms. Twenty-three hours had index values above 420, and all had at least 0.05 mm CLW.

About half of the hours in the moderate 150 to 249 SLIP index range had detectable CLW, and 60 percent of the hours in this range were contained in storm episodes. While this range was neutral concerning the existence of CLW, it contained only 37 of the 390 hours with data. Thus, over 90 percent of all hours were in the low or high SLIP index ranges where the presence of CLW was reasonably well predicted.

5.8.4 False Alarm Ratio. - The false alarm ratio (FAR), expressed in percent, is defined by:

$$FAR = 100 \times (HZ/HT) \qquad (5\text{-}7)$$

where HZ is the number of hours without significant CLW and HT is the total number of hours with a SLIP index greater than zero. For the low, moderate, and high probability ranges above, the false alarm ratios were 90, 46, and 15 percent, respectively.

The SLIP index, as presently defined, correlated well with periods of sustained CLW production during the 1987 winter field season and might be used as an aid in forecasting the development of CLW-producing conditions in future seasons. Conditions specific to the Happy Jack site were utilized in the development of the index so it is probable that any radiometer site change would necessitate modification of the index to suit conditions at the new site. For example, CLW was never sustained at Happy Jack at surface temperatures less than -7.5 °C; but at a higher, colder site, this minimum limit would most likely be colder--how much colder would have to be empirically determined.

5.9 Summary

CLW observations were obtained with a microwave radiometer atop the Mogollon Rim of Arizona from mid-January to mid-March 1987 and 1988 at Happy Jack and Hannagan Meadow, respectively. Supporting wind observations allowed estimation of CLW flux over the barrier. Temperature measurements indicated that the large majority of the CLW was supercooled.

Synoptic scale storms produced the bulk of the CLW at both locations. The airflow was usually from the southwest during CLW episodes over Happy Jack although northeasterly upslope flow was also an important contributor on that portion of the Mogollon Rim. The flow was more westerly when CLW was observed over Hannagan Meadow.

Vertically integrated mean hourly amounts of CLW were less than 0.1 mm over half of the time that CLW was detected. The highest value observed was under 0.7 mm; this suggests generally low liquid water contents were common, which was verified by aircraft observations over Happy Jack. Nevertheless, CLW was observed over 400 hours during the two field seasons so, on the average, CLW was present over 100 hours per month.

Durations of CLW episodes varied from 1 to 80 hours, but the seven episodes lasting 30 hours or more accounted for half the observed hours with CLW. The total estimated CLW flux per storm also varied markedly from 0 to 420 million grams per meter of crosswind distance. About 75 percent of the total 1987 flux was due to only three storms, and 35 percent was produced by a single 80-hour episode--locally reported as the heaviest snowstorm in 20 years. The frequency of large storms was less during early 1988 when a single 53-hour episode produced two-thirds of the seasonal flux.

The distribution of hourly CLW flux plotted against the vertically integrated CLW amount showed that most of the total flux was due to the many hours with light to moderate amounts. While flux values were relatively low during these hours, the high frequency of occurrence suggests the flux values should be considered for possible cloud seeding potential. Conversely, since a large fraction of the seasonal flux is concentrated in relatively few very wet hours, a future seeding program should be especially alert to treat such periods.

The total CLW fluxes over Happy Jack in 1987 and Hannagan Meadow in 1988 were compared with mean annual streamflows from the same regions. The 1987 flux was found to be about half the streamflow while the 1988 flux, with few large storms and missing radiometer data, was estimated as 14 percent of the regional runoff. This is an encouraging result especially since the field programs were each of only 2 months duration; this result suggests that significant cloud seeding potential may exist over the Mogollon Rim of Arizona if entire winters were effectively treated.

Using the most comprehensive data set available, an attempt was made to develop a scheme for predicting the presence and magnitude of CLW over Happy Jack. The scheme finally developed was reasonably successful in predicting the presence or absence of CLW but explained only 29 percent of the variance in CLW amount. This fact, combined with the experience of several missed weather forecasts during the two Arizona field seasons (similar to past experiences in other mountainous areas of the West), indicated that a "nowcasting" program will be essential to future cloud seeding projects over the Mogollon Rim; that is, the important weather factors, such as presence of CLW, will need to be monitored continuously in real time and rapidly responded to as required.

6. CLOUD MICROPHYSICAL, PRECIPITATION, AND STABILITY CHARACTERISTICS

6.1 Aircraft Microphysical Observations

The flight patterns for studying the Arizona clouds were designed more for obtaining a general climatology of cloud conditions rather than for obtaining evolutionary histories of particular clouds. The analyses of the general microphysics of the clouds over the Mogollon Rim therefore were reported in a statistical style, often expressing the frequency with which certain conditions were encountered. Sometimes the data were partitioned into the SS, SC, MS, and MC categories of storm types, as defined in section 4.3. Usually, the analyses showed little difference between the storm types, in which case all aircraft passes were considered together.

All data for this study of general microphysical conditions were restricted to a horizontal area or "box" 10 by 15 km extending 5 km east, south, and west of Happy Jack and 10 km north. These boundaries were chosen to confine the observations to the highest terrain, including the minor peak to the north of Happy Jack. The times for every aircraft pass within this box were determined for the entire 1987 field season. Averages of data were made for all such passes. Each pass was labeled with a code indicating the average reverse flow air temperature for the pass because air temperature usually had the strongest influence on the habits of ice particles. All clear air passes were excluded from further analysis. The acceptable passes were trimmed to those portions that had (a) FSSP (forward scattering spectrometer probe) cloud droplet concentrations greater than 3 per cm^3; (b) nonzero 1D-C particle concentrations; or (c) 2D-C IPC average of greater than 0.01 L^{-1}, for at least 2 consecutive seconds (0.2 km) during the pass. Gaps in the clouds with neither liquid nor ice for 10 or more seconds (about 1 km) were also excluded. The judgment of which portions of a pass contained cloudy air (tiny liquid droplets and/or ice particles) was made from time plots of liquid water and of the encounter time of every acceptable 2D-C particle. A total of 158 aircraft passes met these criteria.

The SLW measurements were averaged both over the entire pass and over only those seconds having FSSP concentration greater than 3 particles per cm^3 (FSSP concentrations of 1 to 3 particles per cm^3 are common in clouds consisting of ice crystals only). The 1D-C measurements were averaged both over the entire pass and over those seconds having 1D-C concentration of greater than 0.1 L^{-1}. The 2D-C measurements were averaged both over the entire pass and over only those portions of the pass with a 2D-C concentration greater than 0.01 L^{-1}.

6.2 Aircraft Liquid Water Observations

6.2.1 Liquid Water Sensors and Their Measurements. - The King Air aircraft had four liquid water instruments (see table 3-1), each with its own operating characteristics and problems. Several sensors were used because of known difficulties in measuring SLW with aircraft probes.

The older standard was the Johnson-Williams hot-wire instrument, which was factory refurbished just prior to the field season. This instrument was most sensitive to droplets smaller than 40-μm diameter and had problems if ice built up on the probe. Shifts to negative values during very wet conditions are shown in the data. Negative averages were excluded from consideration in the analyses.

The CSIRO (also referred to as King) instrument also used a hot wire. This instrument theoretically gave better measurements than the Johnson-Williams, especially in the presence of large droplets. The sensor wire broke during several flights probably due to impacts with large ice pellets, which required the exclusion of data from this instrument. Calculation instabilities sometimes occurred and required that CSIRO instrument SLW data from one entire flight be rejected.

A Rosemount icing detector sensed the amount of rime buildup on a cold rod. On this aircraft, the SLW was calculated from the rate of icing based on earlier comparisons with the other sensors. When the mass of ice reached a preset limit, a heater was turned on to melt the ice so the SLW could also be calculated by measuring the time between heating cycles. Unfortunately, the data from this instrument had a sharp rise at the second just before the event detector indicated that the heating cycle had started. No data could be recorded during the heating cycle so averages could be made only over the period from about 2 seconds after the end of the heating cycle to 1 second before the event detector indicated that it had started. Examples were also found in the data where heating cycles were only several seconds apart during conditions of low SLW as indicated by the other instruments. This presumably occurred when the ice was not fully melted and shed from the probe tip; a drop of residual water may have frozen on the tip and prematurely triggered another heating cycle. Such data are unreliable. All data from this probe were excluded from consideration because of the difficulty of the averaging technique and the refreezing problem.

The FSSP measured the liquid water by counting the number of droplets that passed through a laser beam and sized the droplets by the brightness of the scattered light. The instrument appeared to be calibrated properly and was deiced in the normal manner. But the readings were so much lower than those of the other instruments that the SLW data were suspect. Recent discussions with University of Wyoming scientists responsible for this particular probe have indicated that it indeed undersized by about one bin size (3 μm) and appeared to have a significantly smaller sample volume than normal during the field program in question. Therefore, SLW and droplet concentration data from this instrument should be used with caution. However, this was the only instrument that gave a size distribution. A threshold diameter was calculated in the manner of Hobbs and Rangno (1985)--the diameter at which the cumulative concentration, summed from the large sizes towards the small, reached 3 per cm^3. This diameter was helpful in assessing the potential for ice particle multiplication by the Hallett-Mossop mechanism (Hallett and Mossop, 1974), which requires the presence of a significant concentration of droplets larger than about 24-μm diameter.

Three of the passes discussed in section 6.1 were made near 7 km altitude m.s.l. at temperatures of about -41 °C. As expected, no liquid water was detected at this cold temperature; and these passes were excluded from further consideration. No liquid water was detected anywhere on 43 percent of the remaining passes. When averaged only over the portions of each pass with some SLW present, the Johnson-Williams was greater than 0.10 g cm^{-3} on only 5 percent of the passes. The highest average was 0.31 g cm^{-3} on the Johnson-Williams instrument and 0.49 g cm^{-3} on the CSIRO instrument. When averaged over the entire pass, the Johnson-Williams SLW was greater than 0.10 g cm^{-3} on only 2 percent of the passes; and the highest entire pass averages were 0.15 and 0.25 g cm^{-3}, respectively, on the Johnson-Williams and CSIRO instruments. Obviously, the aircraft did not often find large amounts of liquid water above Happy Jack.

Using only the data from those portions of the passes with SLW present, the relationships between the instruments were examined. The Johnson-Williams instrument was used as the standard in spite of its own problems. A least squares fit against the FSSP SLW content found FSSP (g cm^{-3}) = 0.203 x Johnson-Williams +0.00997 with a correlation coefficient (r) of 0.60. The largest FSSP SLW average within cloud was only 0.09 g cm^{-3}. The fit against the CSIRO SLW, when available, found CSIRO (g cm^{-3}) = 1.403 x Johnson-Williams + 0.02065 with r = 0.88. The CSIRO instrument read (on average) about 40 percent higher than the Johnson-Williams instrument and was reasonably well correlated. The FSSP SLW content was only about a fifth of the Johnson-Williams and had less correlation.

Previous studies on the Grand Mesa in Colorado had indicated that the SLW tended to be greatest at the lower flight altitudes (Holroyd and Super, 1984). Accordingly, the Johnson-Williams averages within the Arizona clouds were plotted against altitude and then combined into four altitude bands for summary. The distributions did not appear to have differences that could not be simply attributed to statistical noise; yet there was a tendency for clouds in the SS category to be wetter in the lower levels while those in the MC category were wetter in the upper levels. This would be expected. Those two trends apparently canceled in the combined sample.

The droplet concentration from the FSSP may have had an altitude relation in that the higher concentrations were in the lower layers, but that may only indicate that the air was cleaner aloft. It would have seemed that droplet concentrations might have been inversely proportional to droplet size; but when the threshold diameter was plotted against concentration, no correlation was found. The largest threshold diameter was 26 μm with nearly all threshold diameters smaller than 20 μm. This indicates that the droplet size conditions for Hallett-Mossop ice multiplication were infrequently met; however, the FSSP probably undersized the droplets by about 3 μm, and possibly more.

6.2.2 Representativeness of Aircraft Cloud Sampling. - The above discussion of aircraft measurements of SLW is less encouraging concerning cloud seeding potential than the discussion in section 5 based on microwave radiometer observations. The aircraft sampling often found little or no SLW over the Happy Jack region. Since SLW is the "fuel" needed for successful cloud seeding, the reasons for the apparent discrepancy between the aircraft and radiometer observations are of considerable interest. A possible explanation could be that the aircraft measurements, which are essentially brief "snapshots" of cloud conditions because of limited aircraft on-station time, were not representative of the much longer period of time sampled by the radiometer. Such a bias was noted by Super et al. (1986) in studies over the Grand Mesa, Colorado. Also, aircraft cloud measurements may be unrepresentative because of the inability to sample close to the surface where much of the SLW is likely to be located, especially during periods with strong orographically induced uplift. This problem was encountered during Reclamation's SCPP studies in California.

The general cloud water conditions during aircraft sampling were compared with radiometer observations of CLW during the entire 1987 field season by the following method. First, the cumulative distribution of hourly mean CLW measurements from the radiometer was plotted for all 317 hours with amounts of

0.01 mm or greater and with all rain periods removed (fig. 6-1). Next, those hours that the aircraft made at least one pass (usually two to six were made) through the 10- by 15-km box around Happy Jack (defined in sec. 6.1) were identified, again discarding periods with rain or radiometer amounts less than 0.01 mm. Each such hour was examined further and a judgment made as to the representativeness of the aircraft pass(es); 4 hours were eliminated because either the aircraft pass(es) were at very high altitude or the CLW was well below the hourly mean during the time(s) of aircraft measurement. The cumulative distribution of the remaining 33 hours is also plotted in figure 6-1.

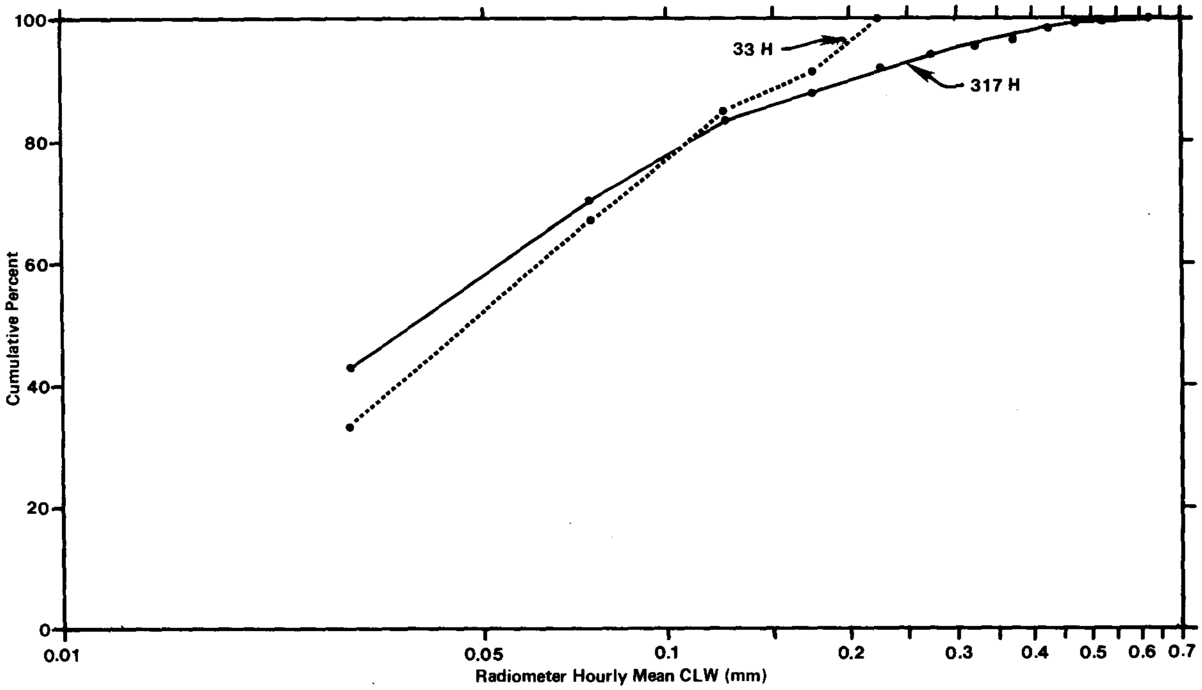


Figure 6-1. - Distributions of radiometer mean hourly CLW for entire 1987 field season (317 h) and for 33 hours with representative aircraft observations.

Examination of figure 6-1 reveals that the two distributions are different. The proportion of aircraft sampling during light amounts of CLW (< 0.1 mm) was less than the seasonal population observed by the radiometer. For example, 43 percent of all radiometer values were less than 0.05 mm, but only 33 percent of the aircraft sampling near Happy Jack was done during such hours. However, of particular importance, the aircraft never sampled during an hour when the radiometer observed greater than 0.22 mm. About 10 percent of the 317 hours of radiometer measurements exceeded this value. While it is not surprising that the wettest 10 percent of the hours were missed by coincidence or for whatever reason (including the grounding of the aircraft for 3 days during the largest storm of the season because of excessive snow on the runways), these hours contributed a large portion of the seasonal flux of CLW as discussed in section 5.7.4. Failure to sample these hours with the aircraft would certainly lead to a less optimistic assessment of cloud seeding potential.

Even if the aircraft had been on station during some of the wettest hours, there is serious doubt whether it could have sampled for an extended period. While the King Air aircraft had all available deicing equipment and was certified for flight into known icing conditions, the amount of airframe icing encountered during the mission of January 31, 1987 (see sec. 7.3.4), suggests that sampling in the wettest clouds must be for brief periods only.

The experience of several 1987 aircraft missions was reviewed by examination of figures 4-2 through 4-9 with aircraft sampling times and altitudes superimposed. Often the aircraft arrived over Happy Jack shortly after a particularly wet or snowy period. After sampling for 2 or 3 hours in clouds of modest interest (if clouds existed), the aircraft returned to base. Soon after the aircraft landed on a number of missions, the clouds over Happy Jack became more interesting again. This is believed to be a problem of response time.

The decision to launch a mission was frequently made immediately after a report from Happy Jack of interesting weather. However, a flight plan was required to be filed 1 hour prior to takeoff. After takeoff, a sounding would be made after which the aircraft would fly over Happy Jack at high altitude and then return for a series of stepped passes from high to low altitude. This was done for reasons of safety to check for unmanageable turbulence or heavy icing. However, the result was that 1.5 to 2 hours could pass from the time interesting weather was first noted until the aircraft started sampling at low altitude over Happy Jack. By that time, the cloud conditions had often changed as can be seen by examination of the figures in section 4. Thus, this response time problem is believed to have resulted in an undersampling of the most interesting clouds and, thereby, an underestimate of cloud seeding potential from aircraft data alone.

A partial solution to the response time problem would have been to use a volume scanning radar to estimate the time of arrival of interesting clouds over Happy Jack (e.g., cloud bands). The Happy Jack vicinity has few adequate radar sites due to the heavy forest cover although one good site was identified near the northeast end of Mormon Lake. However, no nearby electrical power lines existed and resources were not adequate to establish and operate a scanning radar there during the 1987 field season. It is recommended that such a radar be used in support of future experimentation involving cloud physics aircraft.

It is difficult to estimate with the present data set how often SLW was located below the lowest aircraft sampling level of 2.9 km m.s.l. or in what amounts. The radiometer was about 600 m below this level. There was evidence that a significant portion of the total cloud water could sometimes exist in the lowest 600 m above the surface, which would also result in a underestimate of cloud seeding potential from aircraft data alone. For example, the tower-mounted icing meter at Happy Jack indicated the presence of SLW very near the surface during 38 hours over the course of the 1987 field season (the aircraft was sampling down to 2.9 km during only one of these hours). SLW existed well below aircraft sampling levels at least during these hours and most probably during many additional hours. While the hours with icing at tower levels tended to be during periods with high amounts of CLW according to the radiometer, some icing hours had only moderate amounts of CLW. Moreover, several periods with high CLW experienced no near-surface icing; that is, the liquid water did not extend as low as the tower. It is known from experience at other high altitude sites that near-surface icing, even when measured on a high (70-m) tower, can be much less frequent than the occurrence of SLW at somewhat greater heights above the barrier surface (Super et al., 1986); yet there is also evidence that SLW often tends to be concentrated in lower cloud levels (Holroyd and Super, 1984). Therefore, there is good reason to suspect that some (perhaps most) of the SLW frequently exists below the lowest permissible aircraft sampling altitude.

6.3 Observations of Ice particles

6.3.1 Aircraft Observations. - As discussed earlier, ice particle measurements were averaged over each entire pass in the 10- by 15-km box about Happy Jack. Only the 2D-C probe was used, and all accepted particles had to be greater than 0.1 mm in maximum dimension. Average concentrations ranged over four orders of magnitude with the highest averages observed just under 100 L^{-1}. The median IPC was about 1 L^{-1} with the 16 and 84 percentiles (standard deviation from the median) at about 0.1 and 10 L^{-1}, respectively. No consistent differences between the storm types were observed.

The relation was examined between droplet size, as indicated by the threshold diameter, and the IPC. For those passes where the threshold diameter could be defined, there appeared to be a slight tendency for smaller droplets as the concentration of ice particles increased. This is in agreement with the hypothesis of SLW consumption with higher IPC. The lack of any association of large droplets with high IPC again indicated that the Hallett-Mossop ice multiplication process was usually not operating to a significant extent.

The IPC's, averaged over each pass, were examined for relations with air temperature. The properties of the ice particle populations were averaged over all passes having the same air temperature. While the median concentrations mentioned above tended to be about 1 L^{-1}, the average concentrations were about 3 L^{-1} from 0 to -13 °C, then increased to about 10 L^{-1} at -17 °C. At colder temperatures, the trend became noisy because of the small number of samples.

The spectra of ice particle sizes and habits were examined with respect to their contributions to the IPC and to the calculated precipitation rates using the Holroyd method (1987). The precipitation estimates used particle mass calibrations from the Grand Mesa, Colorado. Similar calibrations for Happy Jack indicated that the precipitation rates derived from the aspirated 2D-C probe on the ground should be multiplied by about 1.5 for Arizona conditions. Presumably, the aircraft values should be boosted by the same amount, indicating slightly heavier particles in Arizona.

The first examination was of the entire data set with respect to the air temperature at 1 °C resolution. The concentration spectrum was dominated by small, generally round particles while some had a limited degree of branching. The median size for particles greater than 0.1 mm was about 0.4 mm. Particles greater than 1 mm were only about 10 percent of the population. The ice particle population spectra varied only slightly with temperature, suggesting that the particles were simply settling through the atmosphere and were experiencing limited growth. This would be expected for the limited SLW amounts usually present at the times and altitudes of aircraft sampling.

The spectra with respect to contributions to the calculated precipitation rate showed a different relationship, as is usual. Particles greater than 1 mm contributed the most to the precipitation rate at temperatures warmer than -20 °C but were nearly nonexistent at colder temperatures. Aggregates made large contributions at temperatures within or warmer than the dendritic growth zone (-13 to -17 °C). Snow pellets (graupel of low density) contributed nearly a like amount as aggregates. Irregular particles were the next largest contributors, accounting for 30 percent of the precipitation rate in the dendritic growth zone where irregular particles were likely to represent broken and malformed dendritic crystals. Linear particles were minor contributors to the ice particle population but were usually found at temperatures warmer than -10 °C, indicating that linear particles were needles or columns. In general, there was a tendency for the largest particles contributing to the precipitation rate to increase in size as the temperature became warmer. This could be indicative of particle growth by diffusion, accretion, and/or aggregation as the particles fell through the atmosphere.

Most samples of the ice particles were made on passes with no SLW or insignificant amounts. Therefore, the particles could not have been growing rapidly. A smaller data set was assembled, confined to those passes where a threshold diameter was definable in FSSP droplet spectra averaged over the entire pass. The reduced sample size required a reduction in temperature resolution to only 2 °C. The spectra did not appreciably change from the general conditions. There was a slight tendency for an increase in size of particles contributing to the precipitation rate. Aggregation, which was still prominent at and below the dendritic growth zone, had a second maximum in the needle growth zone. The graupel particles were major contributors to the precipitation rate at about -2, -10, and -18 °C.

In general, the IPC measurements indicated that the nucleation mechanism was one of primary nucleation; the ice particles resulted from activation of ice nuclei. Secondary nucleation mechanisms (ice multiplication processes) did not appear significant in this data set. This indicated that the Arizona winter clouds were more favorable for ice phase cloud seeding than winter clouds in California or tropical summer clouds, for example.

The IPC's were mostly 0.1 to 10 L^{-1} with a median of 1 L^{-1}. At these concentrations, there will be many conditions under which the available ice particle population will be unable to exhaust the supply of liquid condensate resulting from even the smallest reasonable updraft speeds over mountain barriers (Rauber and Grant, 1986). This is again an indicator that ice phase cloud seeding has an opportunity to utilize the excess condensate. Unfortunately, the discussion of representativeness of aircraft cloud sampling (sec. 6.2.2) means that the ice particle measurements discussed above may not be representative of wetter clouds. Only further sampling can clarify the issue.

6.3.2 Surface Observations by the 2D-C Probe. - It was attempted to continuously operate an aspirated 2D-C particle imaging probe at both Happy Jack and Hannagan Meadow whenever there was a possibility of precipitation. The instrument therefore sampled nearly all possible conditions, with some missing observations resulting mostly from power failures. There were 167 hours of data from Happy Jack and 109 hours from Hannagan Meadow. Most power outages occurred at the latter site and were usually associated with the more intense snowfalls. The data set includes those 1987 major storms in which the aircraft did not or could not fly as well as the trivial showers that did not justify an aircraft mission. Periods of rain and slush were excluded from this summary.

The Holroyd (1987) 2D-C analysis software was used to make 15-minute summaries of the snow particles as they were continuously sampled at the surface. There are limited differences in the data between the two sites that seem to reflect only differing sampling opportunities and not fundamental differences in snow characteristics. Therefore, the data from both sites are grouped together in the following discussion.

The ground IPC's were mostly in the range of 0.2 to 200 L^{-1} with a median of 22 L^{-1}. These values were much higher than the IPC's sampled by the aircraft during 1987. There are several possible reasons for this. As discussed in section 6.2.2, the aircraft did not sample the wettest and probably most intense storms, which on the ground may have been dominated by high IPC's. Some of the ice particles observed at the aircraft levels could have undergone collisional breakup as they fell to the ground, especially at high concentrations. Lower level moisture supersaturations might have resulted in nucleation of additional ice embryos. The approximate -5 °C peak for secondary ice multiplication by the Hallett-Mossop process could have occurred between the aircraft sampling level and the ground, boosting the concentrations of embryo ice particles. But multiplication by that process did not appear to ever operate efficiently in the storms sampled. Lastly, ground observers noted ice particle and especially aggregate breakup within the aspirator on several occasions. Ice particle collisions with the sides of the aspirator and shearing of aggregates in the accelerating airflow broke up some particles into smaller pieces. But such an increase in IPC might be expected mostly in sizes greater than about 1 mm rather than in the few hundred micrometer sizes where much of the increase actually occurred.

Because of the various natural and instrument-caused crystal enhancement processes, the amount of real increase in IPC between the aircraft levels and the ground cannot be determined with the present data set. Even simultaneous observations would not have been conclusive because the snow sampled by the aircraft above Happy Jack fell downwind rather than at Happy Jack.

The median size for ground-sampled ice particles greater than 0.1 mm was about 0.27 mm, noticeably smaller than 0.4 mm measured by the aircraft. Such small sizes are considered embryo particles; i.e., quite young. This strengthens the argument for additional nucleation of ice particles between aircraft sampling levels and the surface. The increase in ground IPC's at small sizes was so great that particles greater than 1 mm were less than 1 percent of the population, compared to about 10 percent at aircraft levels. Rauber (1987) described similar characteristics for the Park Range of Colorado. He pointed out that the most common feature of the distribution of ice particles was an increase in IPC's associated with the mountain crest and at lower altitudes in the clouds. (Both Happy Jack and Hannagan Meadow are crest locations at altitudes of about 2.3 and 2.8 km m.s.l, respectively. The lowest aircraft sampling altitude over Happy Jack was near 2.9 km m.s.l.). In particular, Rauber noted that the primary contribution to IPC enhancement near the mountain was from small particles ($< 300\ \mu m$). The Arizona observations are therefore in agreement with those from Colorado.

Particles greater than 0.6 mm contributed the bulk of the surface precipitation mass, with particles greater than 0.9 mm contributing the upper half of the total precipitation. Again, these are smaller sizes than observed at aircraft levels because of the marked increase in the surface concentrations of small particles.

The contributions of the various ice particle types or habits to the larger precipitation rates were examined at the two ground sites. Only those 15-minute periods in which the calculated precipitation rate exceeded 0.1 mm h^{-1} were included in the summary. (Because Arizona snow particles appeared to be more dense than the Colorado particles used to calibrate the 2D-C probe precipitation rate estimates, the actual threshold was probably about 0.15 mm h^{-1}.) Then only those habits making a "significant" contribution of at least 0.01 mm h^{-1} to the precipitation rate were tabulated.

The "irregular" particles as classified by the Holroyd (1987) computerized method produced more snow than any other class. Rauber (1987) found that irregular crystal habits also dominated Colorado mountain snowfall. Irregulars were followed by the "hexagonal," "aggregate," and "graupel" classes. The "linear" and "dendritic" classes made relatively minor contributions. The "tiny" class contributed only during the heaviest snowfalls because of the great numbers of such otherwise insignificant particles. Only during one graupel shower at Hannagan Meadow was the "spherical" class a contributor.

It must be remembered that the particles were computer-classified into the noted categories and that these assignments did not always agree with visual observations. The latter can view entire crystals in three dimensions while the 2D-C images are only two dimensional, and often only a portion of an individual particle is imaged in the 0.8-mm wide field of view of the 2D-C probe. Visual examination of the 2D-C images (not actual particles) suggests that the following interpretations appear to be valid for the Arizona samples. The "tiny" class was properly named and probably did not contain drizzle droplets. The "spherical" class was too rare for comment, except for its association with graupel. The "graupel" class included graupel-like snow of lower density and any large, generally round images of particles that may or may not have been rimed. This class made significant contributions to the precipitation rate over 85 percent of the time during the high snowfall rates. The combined "linear" and its subset of "oriented linear" particles were mostly columns or needles at the surface; these particles are special indicators that storms are making use of low-altitude moisture at temperatures of about -4 to -9 °C. Such particles made significant contributions to the precipitation rate about 60 percent of the time in this summary. The "hexagonal" class was made up of small rounded images with few features. Actual hexagonal symmetry was not tested by the computer software, though such images are typical of the hexagonal plate class. This class made significant contributions over 96 percent of the time to the high precipitation rates. "Dendritic" images were usually of dendritic particles. But during needle snowfalls, the small needle aggregates were classified as "dendritic" or "irregular." Transparent hexagonal plates and small aggregates sometimes were included in the "dendritic" class. This class made significant contributions only about 45 percent of the time at Hannagan Meadow and about 65 percent of the time at Happy Jack. This apparent real difference most likely is attributable to the normal variability of storm situations. The "aggregate" class can contain large dendrites and fluffy graupel-like snow, but it is usually true to its name. The significant contributions from this class occurred 83 percent of the time at Hannagan Meadow and 95 percent at Happy Jack, reflecting the natural variability of dendrites. Rauber (1987) points out that aggregates were usually associated with dendrites in the Colorado clouds, but aggregates of needles (descriptively called "haystacks" by some observers) were common during some intense needle snowfall periods in Arizona. The "irregular" class contained many types of particles, including true irregular particles, broken dendrites, spatial particles, small aggregates, and general "junk." This class made significant contributions to the high precipitation rates over 98 percent of the time.

Most major snowfalls consisted of a smooth spectrum of particles that were mostly in the tiny, hexagonal, irregular, and graupel classes. The images were generally rounded with some irregularities and a continuous range of sizes. Special snowfalls were those with a large component of needles or columns, those primarily of graupel, and those mostly of dendrites and aggregates. While it would be possible to categorize the seasonal snowfall into these four major types, such a summary was not developed for this report partially due to uncertainties in the computerized habit classification. Any general snowstorm can have the snow particle types change during the storm in response to the altitudes (and temperatures) at which moisture is available for particle growth and in response to convective or stable cloud regimes passing over the site.

6.3.3 Visual Surface Observations. - While technicians operated equipment at Happy Jack during early 1987, Reclamation meteorologists were stationed at the Hannagan Meadow site during the 1988 field season. In addition to monitoring the various instrumentation systems, the meteorologists, all trained in cloud physics, made periodic visual observations of the ice crystals settling on a dark surface. These observations were not made on a regular schedule but whenever opportunity permitted.

The observed crystal types (habits) and their degree of riming were noted on 120 separate occasions during the course of the 1988 field season. Riming refers to the accretional growth process; that is, growth by the freezing of cloud droplets on the relatively large ice particles falling through the cloud. Snowfall rates varied from very light to heavy at observation times.

The visual ice crystal data have been tallied to yield a general portrayal of snowflake characteristics. While these data represent spot samples, rather than the continuous 2D-C measurements discussed in section 6.3.2, the visual observations of crystal habit are believed to be more accurate than computer classifications of 2D-C images. Also, riming information is not available from the 2D-C data.

Table 6-1 was created by noting the number of times each ice crystal type was observed. Often, only a single type was noted at a particular observation time while two or more types were seen at other times. Whatever the number of habits observed at a given time, each observation of a particular crystal type was given the same weight. Irregulars were not normally noted, even though they were common, unless it was unclear from the rest of the crystal population what the irregulars were probably derived from. The irregulars were normally pieces of dendritic crystals.

Table 6-1. - Hannagan Meadow ice particle observations

Type	Number of occurrences	Percent of total
small particles	17	10
needles	16	9
plates	0	0
columns	1	< 1
stellars/dendrites	41	23
spatial dendrites	7	4
irregulars	8	5
aggregates	36	20
graupel	50	28

Table 6-1 shows that graupel snow (also called snow pellets) was the most common, comprising 28 percent of all observations. These pellets were of low density and could easily be crushed between fingertips. Dendrites and stellars were noted in 23 percent of the observations followed by aggregates with 20 percent. The aggregates were usually composed of stellars or dendrites, but needle aggregates were seen on occasion.

Columns were seen only once and plates not at all. The 10 percent "small crystal" category may have had some columns and plates; but the particles were usually too tiny for identification, even when using a low magnification hand lens. High magnification (microscope) classification was not attempted.

Ignoring the graupel and small particles, almost all other crystals observed were dendritic in form, meaning that most of their mass development was in the -13 to -17 °C temperature range known to produce rapid growth. It is likely that at least some of the graupel formed by heavy riming of dendritic forms.

The absence of columns and plates is surprising. As the observations were made by trained meteorologists well aware of such crystal forms, it was concluded that such crystals were rare during the 1988 field season. Such crystals can develop at temperatures either warmer or colder than the dendritic forms. When the crystals form at colder temperatures, higher in the atmosphere than the dendritic growth zone, they may be converted to dendritic forms while falling through the -13 to -17 °C layer or become heavily rimed producing graupel. Apparently, columns and plates rarely formed in the -8 to -12 °C layer, unless they either sometimes formed the interior of graupel and therefore could not be identified, or were usually too small to visually identify by habit (some of the small particles of table 6-1).

The degree of ice crystal riming was also tallied. Thirty-seven percent of all observations failed to note any riming. Light riming was observed 14 percent of the time, moderate riming was noted in 5 percent of the cases, and heavy riming (often graupel) was seen 44 percent of the time. The amount of riming was compared with 6-minute means of radiometer observed CLW at corresponding times. Moderate or heavy riming was usually associated with CLW values above 0.10 mm while light riming was rarely seen if the CLW exceeded that amount. Cases without visible riming were mostly associated with the absence of CLW and rarely found with CLW values above 0.05 mm. Several cases of heavy riming had little or no detectable CLW, presumably because the accretional growth took place some distance upwind of Hannagan Meadow as the particles fell on their quasi-horizontal trajectories. Such cases may represent a very efficient natural snowfall process where all cloud liquid is converted to ice before the cloud mass passes the crestline observing site. Hence, observations of rimed crystals, which indicate the presence of supercooled liquid cloud droplets somewhere along the crystal trajectories, does not necessarily mean that seeding potential exists. However, the rimed particle cases with CLW still above the radiometer suggest that nature was not completely efficient and that some seeding potential likely existed. About half of all the Hannagan Meadow rimed crystal observations were made with CLW overhead.

6.4 Surface Precipitation Characteristics

6.4.1 General Characteristics. - The ultimate interest in this study is more precipitation (snow) on the ground; precipitation has economic and ecological value. It is therefore appropriate to know the natural characteristics of precipitation--how and when it forms and in what quantities. The data from a network of seven precipitation gauges during the 1987 field season was used in the summaries below.

A few of the precipitation characteristics are listed in table 6-2 according to gauge location. (Because of the predominance of English units associated with data from these gauges, such units will be used in this section in preference to the metric units generally used in this report). About 8 inches of precipitation fell during the period of study. The term precipitation means melted water equivalent of the snow that fell, expressed in terms of depth on a flat surface. Half of all hours with detectable precipitation were at or below the very light 0.02 in h^{-1} rate. Such light rates accounted for about 10 percent of the total amount. The heavier half of the precipitation fell at rates in excess of about 0.09 in h^{-1}, which occurred during approximately 13 percent of the hours with precipitation. Such precipitation characteristics are common during winters at high elevation regions in the Rocky Mountains.

Table 6-2. - Precipitation characteristics from the early 1987 network.

	Stations						
	1	2	3	4	5	6	7
Total hours with measurable precipitation:	187	247	257	192+	160	149+	230
Total precipitation (inches):	6.660	7.770	8.713	9.765+	6.765	5.910+	8.185
Half of all hours with precipitation are at hourly rates up to (in h^{-1}):	.015	.015	.016	.020	.020	.020	.015
The lighter half of all hours with precipitation account for (percent) of the total:	11.0	10.6	7.9	9.9	9.7	11.5	11.3
Half of all precipitation falls at hourly rates of at least (in h^{-1}):	.090	.075	.080	.125	.100	.085	.075
The heavier half of total precipitation falls in (percent) of the hours with precipitation:	12.6	12.1	12.2	12.9	13.4	14.5	14.5

Stations: 1 - Flagstaff Arboretum; 2 - Mormon Lake; 3 - Happy Jack (0.002 inch resolution); 4 - Baker Lake (some missing data); 5 - Mingus Mountain; 6 - Blue Ridge (some missing data); 7 - Willow Spring.

Six of the gauges had 0.005 inch and one had 0.002 inch resolution. The Mingus Mountain site was on a different mountain range to the west of the Mogollon Rim and therefore experienced different timings of precipitation events than the other gauges. Even on the Mogollon Rim, the geographic span of the sites allowed some gauges to receive precipitation while it had ceased or not started at other gauges.

A timeline was created on which the occurrence of measurable precipitation was plotted. Precipitation at hourly rates that contributed to the lighter half of the total precipitation at each gauge was shaded in one color while that for the heavier half was shaded in another. The data from all seven gauges were plotted beside each other in the resulting figure (not shown). It was apparent that the precipitation fell in episodes typically lasting about 24 hours with longer periods of dry weather in between. The length of the precipitation episodes ranged from a 1-hour shower to the 3-day storm in late February 1987. The precipitation totals from the latter storm are thought to have a recurrence rate of about once every 20 years.

There were times when the precipitation was widespread and produced measurable precipitation at all stations. At other times, as for cumuliform events, not all stations were receiving precipitation at the same time.

6.4.2 Heavy Precipitation Periods. - The time periods during which the heavy precipitation rates (contributing half of the season total amounts) were observed at one or more gauges are presented in table 6-3. Summaries of those storm periods are given in the appendix but with different sequence numbers. In table 6-3, the column labeled "A/C?" identifies those heavy precipitation periods for which aircraft measurements are available (only four were sampled). To the right of the time periods, a column (labeled "# station-hour") identifies the total number of hours, summed over all seven gauges, that the storm produced precipitation at the higher rates at each gauge.

Table 6-3. - Time periods with heavy precipitation at one or more gauges during the 1987 field season.

Storm period	A/C?	Date time to date time	# station-hour heavy precipitation	Cold front	Trough	Low	Tops
1	no	1-15-87 1500 to 1-15-87 2400	10+	post	pre	—	high
2	no	1-16-87 0800 to 1-16-87 0900	1+	post	post	—	low
3	no	1-19-87 1800 to 1-19-87 2200	3	post	axis	—	high
4	yes	1-30-87 1900 to 1-31-87 0100	14	post	pre	—	high
5	no	1-31-87 0100 to 1-31-87 0800	18	(spiral band)	—	pre	high
6	no	1-31-87 1200 to 1-31-87 1700	2	—	post	post	low
7	no	2-17-87 1900 to 2-17-87 2000	1	—	—	—	low
8	no	2-19-87 1900 to 2-20-87 0900	6	—	axis	post	high
9	no	2-23-87 1900 to 2-24-87 2000	86	pre	—	—	high
10	no	2-24-87 2100 to 2-25-87 0400	5	post	axis	—	high
11	no	2-25-87 1600 to 2-25-87 1700	1	post	axis	—	high
12	no	2-26-87 0400 to 2-26-87 1500	5	—	post	post	low
13	yes	3-7-87 0900 to 3-7-87 1000	1+	—	—	axis	high
14	no	3-8-87 1700 to 3-9-87 0100	7+	—	axis	—	high
15	yes	3-15-87 0700 to 3-15-87 1900	26	pre	—	—	high-low
16	yes	3-16-87 0500 to 3-16-87 1800	11	—	post	post	low

The next columns identify the period with respect to common weather features. "Axis" means that the trough or low was directly over the region. The last column identifies the height of the cloud tops as either high or low as seen from the infrared satellite imagery. High tops are those with temperatures colder than about -30 °C (the warmest temperature threshold at which the photographs are contoured) while low tops are warmer than that temperature. During storm period 15, there was a sudden drop from high to low tops during the time interval.

The two greatest producers of precipitation, periods 9 and 15, were both ahead of a cold front. Strong winds from the southwest were bringing in moisture from the ocean off Baja California and organizing it into mesoscale bands. The efficient dynamics of the cloud bands produced the snow particles somewhere in southwestern Arizona and dumped some of that snow on the Mogollon Rim. The snow fell through some fresh low-altitude SLW over the high ground for a supplemental boost to the snowfall total.

Next in importance was a spiral band around a new low--period 5. The band dynamics seemed similar to those ahead of a cold front.

Periods 1 and 4 were both after the cold front but before the upper level trough. The air ahead of the fronts in both cases was drier and failed to produce heavy precipitation. All of the pretrough periods, whether pre- or postcold front, had high cloud tops at least part of the time.

Heavy precipitation was produced near the axis of the upper level trough in five periods. Three periods (3, 10, and 11) were from cloud bands behind a cold front. Period 8 was in stationary to easterly flow on the west side of a low over New Mexico. Period 14 was from local convection triggered by the axis of the trough. All of these periods had high cloud tops and only a few hours of the heavier precipitation. Cloud tops were all low in the heavy precipitation following the passage of an upper level trough (as in periods 2, 6, 12, and 16). The clouds were usually stratus or stratocumulus decks on the back side of a low. Precipitation processes in such clouds can sometimes be inefficient because ice particles are not settling through the lower decks from the high clouds. Periods 7 and 13 were generally light showers from local convection.

A plot was constructed (not shown) of the precipitation rate at Happy Jack versus the radiometer CLW amount for the same hour. While considerable scatter existed, higher precipitation rates (> 0.08 in h^{-1}) were usually associated with relatively low CLW amounts (< 0.1 mm) because such heavy precipitation was generally efficient in consuming the liquid. The CLW obviously was often not totally consumed, even at the highest precipitation rates.

Examination of ice particle types and sizes by aircraft, and calculations of their fall velocities, indicated that the heavy precipitation usually originated as small ice crystals far upwind and far above the Mogollon Rim. The CLW was likely orographically forced, produced by the uplift of the moist air flowing over the Mogollon Rim under southwesterly flow. The CLW was likely concentrated at low levels. The snow and the CLW were independently produced but interacted at low levels over the Mogollon Rim to result in the heavy precipitation at the surface. The plot of precipitation rate versus CLW amount showed frequent evidence of high CLW amounts but generally light precipitation. These periods may have been the most seedable.

6.4.3 Precipitation and Winds. - The Happy Jack precipitation totals and rates had a relationship with the windspeed and direction. Estimates of hourly winds at about the 700-mb (near 3-km) level were made from all data available (rawinsondes, aircraft, acoustic sounder, pibal, and tower winds). Summaries of the winds were restricted to 30 degrees and 3 m s^{-1} resolution because of the coarseness of the estimates. Hourly precipitation totals over all seven gauges were calculated. The SS, SC, and MS storm type classes were combined; the MC class was considered separately.

Precipitation totals and hourly rates (both summed over the seven gauges) were plotted as a function of wind direction (not shown). The totals and rates were the greatest in the southwest quadrant, reflecting the direction of the moisture source and possibly the wind directions associated with the more efficient storm dynamics (in terms of water production). A significant proportion of the precipitation also came from northerly through easterly (upslope) flow, typically associated with the north and northwest sides of a low.

The precipitation from the MC class was associated only with 700-mb directions clockwise from southeast to northwest. The average precipitation rates, summed over the seven stations, were all less than 0.04 in h^{-1}. Again, the peak was in the southwest quadrant; but all average rates were much less than those of the combined SS, SC and MS classes.

Hourly precipitation from all storm types at both Happy Jack and Hannagan Meadow were also related to low-level wind directions measured by vanes on towers. Only 155 hours of combined observations were available from Happy Jack because tower wind data were not collected until late January 1987. However, these measurements again showed the very strong tendency for heavier precipitation to be associated with southwesterly winds. Only 2 of the 19 hours with rates exceeding 0.10 in h^{-1} were associated with winds other than southwesterly (all 19 hours were SS cases). As a result of this plus the high frequency of precipitation with SW flow, 73 percent of the total Happy Jack precipitation occurred with tower winds between 195 and 240 degrees and 85 percent with winds in the south-to-west quadrant.

The relationship at Hannagan Meadow was not as consistent. Over 52 percent of the total precipitation recorded during 181 hours fell with westerly winds between 225 and 300 degrees, but strong components were also associated with easterly and south-southeasterly winds, respectively. The easterly wind cases were due to two SS type storm periods (February 4-5 and February 18-19, 1988, discussed in the appendix), and the south-southeasterly hours were associated with a limited period of heavy snowfall on January 17, 1988, also an SS storm. Precipitation during the 110 hours with SC classification was almost all with westerly flow.

The 700-mb windspeeds for the combined classes were plotted against the Happy Jack hourly precipitation sum (not shown). There was a large scatter, with a correlation coefficient of only 0.41. (Correlations with tower windspeeds were even lower for both Happy Jack and Hannagan Meadow). This is likely because other processes besides windspeed contribute to precipitation production. But there was a tendency for an increase in precipitation with windspeed. The higher windspeeds had a greater production of SLW (the "fuel" for the precipitation) and probably were associated with more intense storm dynamics.

6.4.4 Precipitation by Storm Type. - The hourly precipitation data from the single high-resolution gauge (at Happy Jack in early 1987 and at Hannagan Meadow in early 1988) were considered for each of the four storm classes described in section 4. The results are summarized in table 6-4. At Happy Jack, the SS class not only had many more hours with precipitation than the other classes but also a higher mean hourly rate. Consequently, 83 percent of the total precipitation was associated with the SS class. That class also produced more total precipitation at Hannagan Meadow in spite of the SC class being more frequent there. Again, the highest mean rate was with the SS type storm periods. (MS and MC periods with precipitation were not observed at Hannagan Meadow).

Table 6-4. - Summary of hourly precipitation for each season by storm class.

	1987 Happy Jack					1988 Hannagan Meadow		
	SS	SC	MS	MC	All	SS	SC	All
Hours with precipitation	182	52	7	16	257	80	110	190
Percent of total hours	71	20	3	6	100	42	58	100
Mean rate (in h^{-1})	.040	.025	.003	.011	.034	.040	.020	.028
Median rate (in h^{-1})	.020	.013	.002	.003	.015	.015	.012	.013
Maximum rate (in h^{-1})	.230	.150	.006	.042	.238	.332	.162	.332
Total precipitation (inches)	7.203	1.306	.022	.182	8.713	3.160	2.244	5.404
Percent of total precipitation	83	15	.25	2	100	58	42	100

While the median precipitation rates were the highest for the SS class at both sites, the rates were limited for all classes with the highest median value only 0.02 in h^{-1}. The median for all classes was about 0.015 in h^{-1} at both locations; therefore, half the hours with measurable precipitation had amounts less than 0.015 inch. Clearly, many hours of very light snowfall occurred on the Mogollon Rim. Similar findings were reported for the higher, colder Grand Mesa of Colorado (Super et al., 1986).

It has already been shown in table 6-2 that the lighter half of all hours with measurable precipitation yielded only 7.9 percent of the total at Happy Jack. The corresponding value for Hannagan Meadow is 9.5 percent. Table 6-2 also shows that half of the total precipitation fell at an hourly rate of at least 0.08 in h^{-1} at Happy Jack. The similar rate at Hannagan Meadow was 0.07 in h^{-1} (at the Grand Mesa, it was 0.06 in h^{-1}). Finally, the heavier half of the total precipitation fell in 12.2 percent of the hours with precipitation at Happy Jack and 12.1 percent of the hours at Hannagan Meadow. These highly skewed distributions, common for mountain winter precipitation, were very similar at the two Arizona sites.

6.4.5 Summary of Surface Precipitation. - The characteristics of the Mogollon Rim winter precipitation were similar to those of high elevation sites in the Rocky Mountains. There were many hours of very light precipitation while the heavier half of the seasonal total fell during only 12 percent of all precipitating hours. Precipitation generally fell in episodes lasting about 24 hours with longer periods of dry weather in between.

The heavier precipitation episodes can mostly be linked to cloud systems that were created by synoptic processes that were largely independent of the terrain of the Mogollon Rim. The heavier precipitation was generally initiated at high levels upwind of the Mogollon Rim, but the precipitation often received an additional boost from locally produced SLW over the Mogollon Rim. As also shown in section 4, even the heaviest precipitation rates were frequently unable to consume all of the SLW while the greatest amounts of SLW were usually associated with the lighter precipitation rates, giving hope for successful cloud seeding opportunities.

Most of the precipitation fell from the SS class with important contributions from the SC and only trivial amounts from the limited number of MC and MS hours. Most of the Happy Jack precipitation was associated with southwesterly flow while some precipitation came during flows from the north through the east. Westerly flow was most important at Hannagan Meadow. There was also a weak relation indicating higher precipitation amounts with higher windspeeds at both Happy Jack and Hannagan Meadow.

6.5 Atmospheric Stabilities

6.5.1 Introduction. - The atmospheric stabilities for central Arizona were examined for mid-January to mid-March 1987 using rawinsonde data from the 0500 and 1700 soundings at Winslow, similar soundings at more frequent times (during storm periods) at Camp Verde, and soundings reconstructed from the University of Wyoming King Air aircraft data. An understanding of the atmospheric structure was sought for guidance in associated analyses of the early 1987 Arizona data base and for planning future Arizona research efforts, including the possible use of a computer model to predict precipitation targeting during cloud seeding experiments. The specific objectives were (a) to use the stability structure of the atmosphere during storm periods to help determine the magnitude of any distortions in the windspeed and/or directions because of the presence of the terrain; and (b) to estimate the possible vertical extent of ground-released seeding materials if released during storm periods.

6.5.2 Consideration of the SCPP Targeting Model. - One computerized targeting model that might be adapted for use in Arizona was designed for use in stable or neutral orographic flow over the Sierra Nevada Mountains of California as discussed by Rauber et al. (1988). As used in Reclamation's SCPP, the model received input from an upwind sounding plus a sounding near the crest. Updates from aircraft observations could also be entered. Flow channels were determined based on an invariant 400-mb upper surface, a 650-mb mid-flow channel that distorted vertically with the calculated flow patterns, and a simplified bottom surface at the ground level. Stagnant air was allowed upwind of the barrier. The model predicted the speed and direction changes in winds over the mountain barrier.

Once the flow field was specified in the SCPP model, the interactions between the microphysical part of the model and the wind patterns determined the predicted fallout positions for snow initiated by aircraft or ground-released seeding materials.

An initial step in adapting the SCPP model to Arizona terrain would require examination of the vertical distortion of the surfaces of equal equivalent potential temperature (θe) near the 650-mb level. This θe is supposed to be invariant within a parcel of air making adiabatic altitude changes even when condensation or evaporation is occurring. Thus, lines of constant θe should also be streamlines for the atmospheric flow. In the absence of water phase changes, the ordinary potential temperature (θ) also remains constant under adiabatic conditions.

Several analysis styles were used to examine the three-dimensional variations of θ and θe in the project area using aircraft data. It was soon found that θe was nearly constant with altitude (up to cloud top) during storm conditions. This means that there was no significant stratification of the air by which θe could be used as a "tag" to identify vertical distortions in the air flow over the crest. It also indicated neutral stability; the air was generally free to move vertically in response to other forces. It would therefore be inappropriate to initiate the flow fields in the SCPP model by searching for a 650-mb θe surface. The atmospheres during early 1987 Arizona storm periods, being neutral, did not meet the model assumptions of stable stratification. Direct specification of the wind patterns independent of θe surfaces would therefore be needed in the model.

6.5.3 Stability Observations for Ground Seeding Plume Rise. - It is appropriate to examine the stability data to estimate if ground seeding appears reasonable for given storm periods. Aircraft measurements at low levels over the Grand Mesa of Colorado (Holroyd et al., 1988) have shown that a vertical temperature profile usually has a variance of one to several degrees Celsius over a several kilometer horizontal distance at a given level. Under these conditions, plumes were observed to rise as long as the warmest potential temperature (equivalent potential temperature for cloudy air) at the release site was equal to or warmer than the coldest potential temperature measured aloft.

Aircraft-determined profiles of θ and θe were examined for every storm case in the data set. The profiles showed horizontal variability of those temperatures similar to the cited Grand Mesa observations. A judgment was made estimating how high a ground-released seeding plume could eventually rise in each atmosphere. If the temperature at the top of the plume was colder than -10 °C, then the answer was "yes" to the appropriateness of ground seeding with AgI. If the plume top temperature was -6 °C or warmer, then "no" was the answer. In between, "maybe" was appropriate depending on whether exotic complexes of AgI nuclei would be used. In some cases, the stability profile could allow vigorous cloud parcels to penetrate into dry air above the general cloud top and thereby improve the chance of successful AgI seeding. Even without such modifications for possible extra vertical penetrations, the initial estimates yielded 17 "yes", 6 "maybe", and 1 "no" over all flights in cloudy conditions. The "no" resulted from conditions that were too warm rather than from stability preventing the seeding materials from reaching cloud top.

There is, however, a possible serious flaw with this approach in that it assumes sufficient time is always available for the ground-released AgI to mix vertically to sufficiently cold levels. In reality, time is often limited by the horizontal wind carrying the seeded volume of air over the barrier before maximum vertical dispersion is achieved. A more realistic approach is given by the aircraft tracing experiments that actually mapped out the volume of atmosphere affected by ground-released gas (sec. 9).

6.5.4 Summary of Stabilities. - A study of soundings of the Arizona atmosphere during winter storm conditions has shown mostly neutral stability, which prevents the determination of air flow streamlines by means of mapping θe surfaces because θe is nearly the same everywhere in the storm clouds. This neutral stability also indicates that, given sufficient time, seeding materials released from the ground may frequently rise to levels and temperatures at which AgI can create an abundance of ice particles in the presence of SLW. Thus, the atmospheric stability is not a limiting factor to vertical mixing as has been found for some mountain barriers in the western United States.

6.6 Winds Aloft

6.6.1 Introduction. - The winds aloft were analyzed from the same data base of upper air soundings and aircraft data as the stability studies. Furthermore, the low-level winds above Happy Jack were measured with a tower-mounted anemometer and vane, an acoustic sounder, and occasional pibals. The specific objectives were (a) to predict the wind profile above Happy Jack using wind profiles measured elsewhere, (b) to determine the magnitude of any distortions in the wind profile resulting from the shape of the terrain, and (c) to determine typical wind fields during storm periods.

6.6.2 Predictors of Happy Jack Winds. - The present version of the SCPP model requires an upwind sounding to help specify the wind patterns over the barrier. The model is aided by a sounding taken near the crest to determine how much air is actually flowing over the crest rather than around the barrier. It was therefore appropriate to try to determine which sounding was most useful in determining the conditions over the crest.

The crest winds were determined by constructing a graph of the winds versus altitude using aircraft wind data whenever the aircraft was within 25 km of Happy Jack. The winds were usually plotted by speed and direction, and the results were essentially scatter diagrams because of the natural turbulence in the atmosphere. A visual average of the winds was made at five altitudes: 3.0, 3.5, 4.0, 4.5, and 5.0 km m.s.l. Similarly, averages of aircraft winds were made from data for the initial ascent out of Prescott and the final descent into Prescott. The same altitudes were used for winds determined by Winslow and Camp Verde soundings closest in time to the aircraft soundings over Happy Jack. The vector differences between the Happy Jack aircraft winds and those of the other soundings were tabulated.

Frequency diagrams of the magnitude of the vector differences (1 m s^{-1} resolution), independent of the direction of those differences, showed that the Prescott ascent soundings had the closest match to the Happy Jack values with 3 m s^{-1} being the most frequent difference. When direction was included, there was no net offset in speed. This close match is understandable because the air mass sampled by the aircraft on its ascent out of Prescott was most frequently the air mass later sampled over Happy Jack.

The descent sounding was in air that had not yet reached Happy Jack, resulting in a slightly greater vector difference. The Winslow soundings were usually downwind and at only 12 hours resolution. A 3 m s^{-1} difference was also most frequent for Winslow soundings, but the distribution was several m s^{-1} broader than for Prescott ascent. The Camp Verde soundings were geographically closer to Happy Jack than the Prescott ascent soundings but were at a resolution no better than 3 hours. The typical vector difference was about 4 m s^{-1} with a distribution as broad as for Winslow.

6.6.3 Distortion of the Happy Jack Winds by Terrain. - On some days, the winds near Happy Jack were highly variable, especially in speed. Studies over other mountains have shown that air can be dammed and thereby have a slower speed upwind of the barrier. The winds can then accelerate to cross the barrier at higher speed (often perpendicular to the crest axis) before slowing to normal speeds downwind of the barrier (e.g., Super and Boe, 1988b). However, the terrain near Happy Jack is of limited relief compared to the other mountains studied; thus, it might be expected that little terrain-induced distortion in the flow would be found.

The aircraft winds were averaged over 10-km wide "bins," with one centered over Happy Jack and the others extending upwind and downwind from there. A vertical resolution of 10 mb was used over 725 to 675 mb-- the lowest flight levels during storm conditions. The winds were expressed as the component parallel to the general flow and the component perpendicular to that flow.

A plot of the parallel component was made versus distance from Happy Jack. A large majority of cases showed little or no speed changes as the air crossed the barrier. However, eight cases showed sharp speed increases of up to 15 m s^{-1} near Happy Jack in a manner typical of some abrupt mountain barriers, usually followed by decreases downwind. But those cases covered the entire range of observed average speeds and were not confined to the higher speed cases; nor were the stabilities unusual in these cases. It is not yet obvious when such accelerated flow should be expected.

A plot of the perpendicular wind component showed variations from near zero to generally less than 6 m s^{-1}. There was a tendency for a change of 3 m s^{-1} in this component in the sense of an anticyclonic curvature as the air passed over the barrier. This could be a normal wind response to the friction imposed by the terrain; yet there were also cases showing no or cyclonic curvature across the barrier. In general, the changes in this perpendicular component were less than the scatter of natural variability.

These studies showed that it is difficult to specify the distortion in the wind field over the barrier on the basis of a sounding in any one location. Our recommendation for the future use of computerized air flow and cloud models is that the models be initialized with an Winslow sounding for general synoptic scale flow and refined at the lower levels over Happy Jack by an acoustic sounder. This allows continuous monitoring of the flow field in the region of interest. Once aloft, an aircraft's wind measurements can be used to supplement the other data and refine the wind field. The aircraft might do a special sounding in the Camp Verde region at the start and end of a mission, but the need for special balloon soundings for upwind measurements is not yet obvious.

6.6.4 Summary of Winds. - The winds measured during the ascent sounding of the aircraft from Prescott were the best indicator of winds over Happy Jack later in the mission. Most flows showed little speed or direction distortion in response to the terrain near Happy Jack. But some limited periods had speed changes of up to 15 m s^{-1} as the air flowed over the Mogollon Rim, for reasons not yet understood. Winds during the most interesting CLW- and precipitation-producing storm episodes were generally from the south to southwest; those from other episodes completed the distribution through nearly all other general directions.

7. CASE STUDIES OF SELECTED STORMS

7.1 Introduction and Analysis Products

A few selected storms are discussed in detail in this section. Only 1987 storms were considered because more comprehensive measurements, including radar and aircraft, were made during that field season. The storms chosen for case study analysis had reasonably good aircraft observations and were particularly useful in illustrating several important features of Arizona winter clouds. These features included spatial and temporal variability, microphysics, and weather modification potential.

Some of the analysis products generated for this section involved a nonstandard viewpoint. As only one example is shown (in sec. 7.3.1), the approach is described in some detail. The viewpoint is related to slit photography, sometimes used in physics applications where a moving film is allowed to see only what is happening with time through a narrow, vertical slit. A distance-time portrayal can then be created.

In this application, one of the products created was a "continuous weather map" for the 700-mb level. The slit is the 112-degree west meridian. The scale on the original figures was such that the time axis was equivalent to just less than 10 m s^{-1} drift speed from the west. The rawinsonde stations (Great Falls, Montana; Salt Lake City, Utah; Winslow, Arizona; and Tucson, Arizona) were offset east or west as appropriate from the slit at their latitudes. In this way, many days of weather observations were plotted on one continuous sheet. Under normal flow, the pressure, temperature, moisture, and wind patterns were interpreted like a normal instantaneous weather map at that level.

Another product was created by viewing successive satellite photographs through a similar slit. The normal SB3 sector was used for uniformity of scale. For continuity during the night, the infrared and contoured infrared photographs were used rather than the visible photographs. The slit style of figure was constructed by one of two methods. In one method, copies of the photographs were cut along an appropriate line, which was the same for all photographs and which went through the Happy Jack area. A mosaic was assembled with each photograph slit edge offset from the others at the same 2 mm h^{-1}. Missing photographs allowed more of the previous photograph to be exposed (essentially a wider slit). The use of the remainder of the photograph on the first and last of a series in the mosaic was equivalent to an extrapolation in time forward or back so that the context of the mosaic in the general weather pattern could be seen. The best continuous satellite photographs were created by aligning the slit perpendicular to the observed cloud motion rather than strictly adhering to a north-south slit.

A second method was faster but crude. Tracing paper was placed over the photographs. Those portions of the photograph within the appropriate slit width were shaded with colored pencils according to the brightness or contouring level. The result was essentially the same as the mosaic method but without the proper fine resolution shading.

Various graphical analysis products were generated with a computer using the aircraft data for each case study analysis, and for each aircraft mission flown during the field season. Since most of these products are not shown, mention is made here. The graphical products, usually done in a variety of colors, included plots of SLW versus altitude and time, aircraft flight tracks plotted on contour maps with each minute noted, altitude-distance diagrams with the distance referenced to a location of interest (usually Happy Jack), and a particular parameter (SLW, IPC, winds, etc.) plotted upon the aircraft flight track. A scale for the parameter and each minute of time were also noted. Other plots included IPC and SLW plotted in separate panels on the same page versus either time or distance and cloud droplet spectra for time periods of interest. In addition, 1-second listings of all aircraft data of interest were produced for each case study mission.

7.2 Aircraft Mission of January 28, 1987

The first in-cloud IFR aircraft mission of the field season took place the morning of January 28. The radar at Happy Jack (2.3 km elevation) first detected a thin cloud deck overhead about 0300 near 5 km m.s.l. altitude, as illustrated in figure 4-3. The cloud deck rapidly thickened approaching its maximum top elevation near 9 km by 0530. At that time, the base was down to 2.9 km. The cloud tops varied between 6.6 and 9.5 km until 1000, after which the cloud was no longer detectable by the radar. Bases reached their lowest level of 2.8 km (500 m a.g.l.) from 0800 to 0900, but no precipitation was monitored by any gauge in the network on this date. Some trace amounts were visually reported at Flagstaff and Happy Jack between 0740 and 0845.

The aircraft first passed over Happy Jack at 0822. That was at the time of the greatest radar reflectivity and just before the cloud deck split into upper and lower decks. All aircraft sampling was done in the lower deck. Peak amounts of SLW in excess of 0.1 g m^{-3} were measured by the Johnson-Williams instrument from cloud top at 5.1 km (-13 °C) by the aircraft descending into the Happy Jack area from the west, until 4.0 km (-6.5 °C) where the first ice particles were observed. Peak IPC exceeded 60 L^{-1} with a mean value near 30 L^{-1} in a small shower that extended to about 500 m below the visible cloud base. The crystals were generally very small (0.1 to 0.2 mm), but occasional 1-mm graupel and heavily rimed dendrites were also observed.

Two along-the-wind passes were made below cloud base. A very weak shower was encountered on the first pass at 2.91 km, but none on the second at 3.21 km near 0845. By that time, no showers were visible anywhere in the area.

Horizontal winds below cloud base were near 240 degrees (all directions referenced to true north) with speeds between 20 and 30 m s^{-1}. Vertical velocities averaged perhaps 1 m s^{-1} upwind of the crestline of the Mogollon Rim but became negative over and east of the crest where the cloud deck quickly evaporated. The exact magnitude of the vertical velocity was not known due to offset errors. The same pattern was evident from cloud base to cloud top. The strong winds (27 m s^{-1} at cloud top) were forced over the high terrain, which was clearly causing the uplift and resulting orographic layer cloud.

Three along-the-wind passes were made near cloud base (3.64 km), cloud top (5.18 km), and at 4.25 km from 0850 to 0920. A higher cloud deck existed well above the 5.18-km level. A wave structure was evident throughout the cloud, which caused difficulty in piloting the aircraft at a constant altitude. SLW values peaked near 0.05 g m^{-3} just above cloud base, at about 0.1 g m^{-3} at 4.25 km, and greater than 0.25 g m^{-3} at cloud top. Similar values were found during two crosswind passes and a final along-the-wind pass just above cloud base near 0957.

The cloud deck was almost ice free except in the lower portion. Each of three passes near cloud base over Happy Jack encountered high IPC over the highest terrain in the -4 to -6.5 °C range. Most of the crystals consisted of needles with some aggregates of needles and occasional small graupel.

To characterize the droplet spectrum, a TD (threshold diameter), introduced by Hobbs and Rangno (1985), was defined by the cumulative concentration of droplets with diameters greater than TD being 3 cm^3 as measured by an FSSP sensor (likely about 1 droplet per cm^3 > TD due to artificial broadening by the instrument). Caution should be exercised in considering the FSSP concentrations to be reported for reasons discussed in section 6, where it is also noted that FSSP droplet sizes (always given as diameters) might have been about 3 μs larger than the measured values to be given.

The TD was about 20 μm near cloud base where a low concentration of cloud droplets greater than 24 μm was observed. Perhaps these largest droplets combined with the occasional graupel to cause ice multiplication by the Hallett-Mossop process. A similar situation was observed on January 31 where again the cloud deck was almost ice free except for the warm temperature needle zone where relatively high IPC developed.

Radiometer observations of SLW were zero prior to 0820 and then rapidly increased to a peak near 0.5 mm about 0900 as the upper cloud separated from the lower deck. Presumably, the higher radar reflectivities and lack of SLW over Happy Jack prior to 0820 (by chance the time of aircraft arrival) were due to the high, cold cloud top providing abundant ice crystals to fully utilize the liquid water. Once the cloud mass separated into two decks, the main ice crystal source for the lower deck was apparently largely eliminated and abundant SLW could exist in it.

The radar could no longer detect cloud overhead after 1000, likely due to an absence of ice particles which are usually much larger than cloud droplets and thereby provide a significantly greater radar return. Yet, the radiometer observed SLW, which generally decreased with time until 1245. The remainder of the day had only scattered clouds.

Hourly mean values of integrated SLW ranged from 0.05 to 0.19 mm between 0800 and 1300 with a mean of 0.10 mm. Using these values together with a measured mean windspeed of 25 m s^{-1} at cloud levels yields SLW flux values from 1250 to 4750 g s^{-1} (for a 1-m crosswind distance) with a mean of 2500 g s^{-1}; this is a significant flux. As noted by Thompson and Super (1987), less than 10 percent of the hours with SLW observed over the Grand Mesa, Colorado, exceeded this value over a 3-month winter period.

The amount of the January 28 SLW flux that seeding might convert to snowfall on the Mogollon Rim, if any, was difficult to estimate. Cloud bases were very high so sublimation losses for falling ice particles could have been considerable. The natural showers that were observed produced only a trace on the ground. However, ice particles were found only in the lower cloud portions by the aircraft. Seeding at higher levels presumably could have resulted in larger particles, perhaps graupel-like pellets with high fall velocities. Another important consideration was the strong winds present (25 m s^{-1} at cloud levels), which would limit ice crystal growth times prior to passage into the lee subsidence (and sublimation) zone. The cloud deck was observed to first form about 40 km upwind of Happy Jack and thicken downwind to the 5.1-km level about 25 to 30 km upwind. The most appropriate seeding approach would likely have been to release AgI from aircraft some distance upwind of the cloud's leading edge.

Embryonic ice crystals caused by seeding would be expected to grow while traveling in quasi-horizontal trajectories with their ice crystal settling velocities initially more than balanced by the upward component of the air flowing over the Mogollon Rim. For southwesterly flow, the slope of the terrain upwind of Happy Jack is about 0.025 so a mean vertical velocity of about 0.6 m s^{-1} could be expected with 25 m s^{-1} horizontal flow. Aircraft-measured positive vertical velocities were clearly evident at all altitudes upwind of the Mogollon Rim and downdrafts beyond, but the magnitudes were in question because of an offset error of unknown amount.

Assuming large aggregates or graupel-like pellets would form about 10 to 15 minutes after nucleation, their settling velocities of 1 to 2 m s^{-1} would be well in excess of the net upward motion approaching the crest. By that time, such particles or pellets should still be about 20 km upwind of Happy Jack assuming nucleation near the cloud's leading edge. Given a net fall velocity of 1 m s^{-1}, a particle would fall 800 m while traveling the remaining 20 km. Since cloud base was 500 m about Happy Jack, it was conceivable that some seeding-induced snowfall could have reached Happy Jack though likely most would have fallen farther downwind in the Little Colorado River drainage.

The above calculations are crude and could be improved by existing computer models calculating growth rates as a function of temperature, estimating the entire flow field, etc. However, uncertainties would still remain in any precipitation estimates due to present limitations in knowledge (e.g., would the precipitation have induced downdrafts significant to the ice particle trajectories?). It is recommended that actual seeding experiments be conducted to determine whether high-based clouds similar to those of January 28 are suitable for snowfall augmentation. Whatever the outcome of future experiments, this case study has documented the existence of orographic clouds with little natural IPC (except in the needle growth region) and significant SLW flux. Similar clouds with bases at ground level should be seedable; the case study of January 31, 1987, demonstrated such a situation.

7.3 Aircraft Missions of January 30-31, 1987

A 24-hour period of almost continuous SLW production over the Happy Jack region commenced at 1500 on January 30 and was caused by a 500-mb trough, which moved inland over California and closed over southern Arizona by 0500 on January 31. The low-pressure center tracked south of Happy Jack, essentially over Phoenix. Prevailing wind directions were southerly or southwesterly prior to about 2000 on January 30 and afterwards became northerly or northeasterly causing an upslope condition over the Happy Jack area.

Precipitation, as measured by the high-resolution Happy Jack gauge, did not start until 1900 on January 30 and remained light until stopping at 0200 on January 31. A 3-hour period of heavy snowfall, with water equivalent rates of 3 to 5 mm h^{-1}, occurred from 0300 to 0600 on January 31. This was coincident with a wind direction shift from northerly to west-southwesterly. By 0600, Happy Jack winds were again northerly; only very light snowfall occurred thereafter.

Two aircraft missions were flown during this storm. The first mission sampled conditions early in the storm and, unfortunately, mostly during a period with a large hole in the cloud deck over Happy Jack itself. The second mission observed a period with a widespread shallow cloud deck, abundant SLW, and very light snowfall. The storm will be discussed as it evolved with time, with each aircraft mission interjected in the discussion at its time of occurrence.

7.3.1 Satellite Photograph Pattern for the Storm of January 30-31, 1987. - A slit presentation of contoured infrared images was created with an orientation from the northwest corner of Arizona through the Happy Jack area and to the southeast. This slit was approximately perpendicular to the mean cloud motion associated with the frontal clouds and is presented in the lower part of figure 7-1; the upper parts of this figure are simplifications of figure 4-4 but with the time axis reversed. The dotted line in the lower part of figure 7-1 represents the track of Happy Jack beneath the clouds. The vertical lines are the time axes by which the upper parts of the figure connect with the lower.

The clouds showed a "hole" ahead of the frontal band in the Happy Jack region, as was observed by the aircraft data. That hole may have been caused by subsidence adjacent to the strong thundershower (darkest shading) that passed northwest and north of Happy Jack. Later, the aircraft flew in the frontal band and experienced a wind shift from south-southwesterly to south-southeasterly directions. The positions of aircraft passes in this storm are shown as small circles superimposed on the radar patterns. The aircraft did not penetrate the intense parts of the storm.

The surface instruments showed moderate snow and radar echoes with moderate liquid water in the postfrontal clouds. After midnight, there was a gap in the clouds seen by the radar and satellite photographs. Near sunrise on January 31, another band, arcing as an inner spiral arm around the new low-pressure system, arrived over the project area. Comparison of the sequence of satellite photographs showed obvious rotation of the cloud band around the center of the low. The southern edge of the clouds was sharp while the infrared contouring indicated a tall cloud system. The Happy Jack radar observed this cloud region, which had a little liquid water directly above Happy Jack and a heavy snowfall rate. Presumably, this cloud region was a tall convective system with convergent inflow and a SLW region just north of Happy Jack (there was a surface windshift from northerly to southerly for about 2 hours as the spiral band passed overhead and then back to northerly). The system dumped its precipitation on the south side of the inflow.

7.3.2 Aircraft Mission of January 30, 1987. - Figure 4-4 illustrates the variation of CLW with time. The diagonal portion from about 1930 to 2100 on January 30 represents linear extrapolation during a period of erroneous data caused by a wet reflector (melting snow) as the surface temperature was greater than 0 °C until 2400. Thereafter, the radiometer CLW was entirely supercooled (SLW) through the remainder of the storm.

Vertically integrated water vapor began to rapidly increase over Happy Jack after 1330 on January 30 and remained at high levels until after 1600 the following day. CLW first occurred from about 1530 to 1800 and

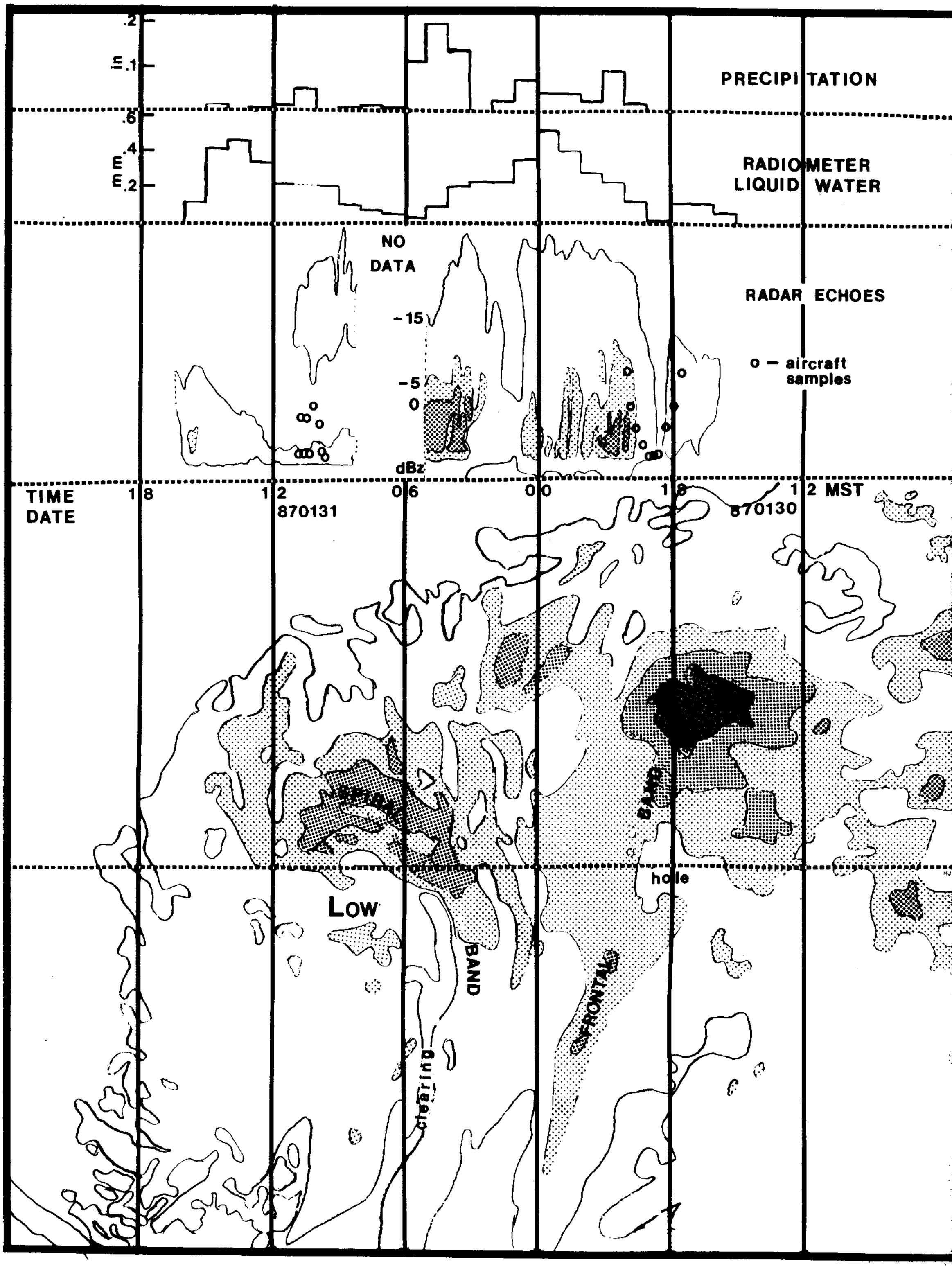


Figure 7-1. - A time plot of the major observations of the storm of January 30-31, 1987. The lower part of the figure is a slit analysis of the satellite photographs. The upper part presents the data of figure 4-4. In this figure, time increases to the left.

was quite variable; this coincided with reports of stratocumulus from the Flagstaff airport NWS station, which reported a scattered to broken cloud base near 3.5 km m.s.l.

The time-height radar observations from Happy Jack (fig. 4-4) showed a continuous deck during this interval, with bases descending with time from 3.8 to 2.8 km (ground at 2.3 km). Tops increased with time from 5.5 km at 1600 to 6.2 km at 1800, after which a "gap" occurred. (The air crew reported at 1800 and again at 1852 that Happy Jack was in a large hole in the general cloud deck.)

The aircraft departed from Prescott at 1716 on January 30 with virga and light showers in all quadrants. The aircraft proceeded toward the Happy Jack area, making a sounding to 5.2 km on the way. The atmosphere was neutral up to about 3.2 km but stable above. The potential temperature increased from 300.5 degrees K at 3.2 km to 311.5 degrees K at 5.2 km. Generally, the wind direction was southerly at all levels with speeds increasing from about 6 m s^{-1} at 2 km to 9 m s^{-1} at 3 km to 21 m s^{-1} at 4 km with little increase thereafter. A marked increase with height existed just above the neutral layer. No SLW cloud was observed on the initial sounding, but ice particles were common.

Some weak patches of liquid cloud that were almost ice free were observed at 5.2 km (-15 °C) while approaching and crossing the Mogollon Rim near Happy Jack. Continuous SLW was first encountered while descending through 5.0 km, setting up for the first parallel-to-the-wind pass over Happy Jack. The Johnson-Williams probe SLW contents reached 0.15 g m^{-3} near 4.6 km. The first pass was at 4.29 km, and SLW cloud was generally continuous from 7 to 26 km north-northeast of Happy Jack; that is, over the top of the Mogollon Rim. Amounts were usually near 0.1 g m^{-3}. Some peak IPC exceeded 20 L^{-1}, but the mean was only a few per liter. Liquid cloud and ice crystals were quite spotty over the southern flank of the barrier, and SLW was nonexistent south of about the 2.1-km contour.

Further passes were made parallel to the wind at 3.68, 3.24, and 2.94 km, but essentially no SLW was observed. Ice crystals were intermittently encountered with peak concentrations about 15 L^{-1}, but a large hole in the general cloud deck existed over Happy Jack at this time (1800 to 1850). Soon after, the radar and radiometer indicated a rapid increase in cloud thickness and vertically integrated CLW.

A second series of along-the-wind passes was made from 1853 to 2005 at five altitudes starting at 2.94 km and ending at 5.19 km. This series was more representative of the beginning phase of the storm than moving into the area.

The lowest pass detected no SLW but almost continuous ice particles with a few peak concentrations greater than 10 L^{-1}. Some patchy liquid cloud was first encountered at 3.25 km along the southern portion of the pass with accompanying peak IPC greater than 20 L^{-1} although the mean was only 2.6 L^{-1}. Many of the ice particles were aggregates; some dendrites greater than 10 mm were common. Lower IPC and no SLW were found farther north. The same general situation was true for the 3.66-km pass, which monitored spotty SLW clouds south (but none north) of Happy Jack. Amounts were usually less than 0.1 g m^{-3}. However, peak IPC was then exceeding 30 L^{-1} to the south of Happy Jack. In contrast, on the next pass at 4.29 km, liquid cloud existed from about 15 km south-southwest of Happy Jack to the end of the pass 35 km north-northeast of it. The SLW was continuous north of Happy Jack with amounts generally from 0.05 to 0.15 g m^{-3}. The value of TD in this region was 16 μm with a droplet concentration of 43 per cm^3. This indicates most cloud droplets were small so ice multiplication by the Hallett-Mossop process was unlikely and the clouds colloidally stable. The IPC was high along the entire pass with many peaks above 30 L^{-1}.

Dendritic forms were common on this entire series of passes as were aggregates, often several millimeters in size and usually composed of dendrites. Many of the ice particles had rounded shapes, suggesting some riming. Graupel-like particles were predominant on the wetter portions of the 4.29-km pass north of Happy Jack. The final pass at 5.20 km detected very little SLW, but widespread ice with IPC generally from 5 to 30 L^{-1}. The temperature was -15 °C.

Clearly, the SLW amounts were limited and the distribution variable at this beginning phase of the storm; but most SLW was observed near 4 km altitude and north of Happy Jack. Essentially, no liquid cloud existed at the lowest level sampled, 2.94 km.

The mission was flown during a period of rapid change in conditions and was unlikely to be representative of the several hours following that were characterized by large CLW amounts according to the radiometer. From vertical radar measurements, the cloud deck thickened rapidly as the mission was ending, with radar tops exceeding 5 km by 1930. The rapid development of the storm was not apparent to the air crew due to darkness.

7.3.3 Between the Aircraft Missions. - After about 1915, the CLW increased rapidly as the cloud deck thickened. Radar tops reached 8 km by 2000 and remained near that level for several hours. Cloud tops almost certainly were composed only of ice crystals because the cloud tops were colder than -40 °C. In spite of cold icy cloud tops, one of the two peak periods of CLW production took place from 2000 to 0400. The vertically integrated amount of CLW was partially related to the low-level winds during this time. Acoustic sounder winds were monitored in the lowest 600 m above Happy Jack. The 300-m a.g.l. (2.6-km m.s.l.) winds were representative during this storm and were used unless otherwise stated. The winds were from the southwest from 1500 to 2000 with speeds between 5 to 8 m s^{-1}. The direction shifted at 2000, reached north by 2030, continued to veer to northeast by 2200, and remained there until 0300 on January 31. Speeds remained from 5 to 8 m s^{-1} until 2215 and abruptly increased to the 10 to 14 m s^{-1} range until 2400. Speeds then increased even more, ranging from 15 to 18 m s^{-1} between 0000 and 0300 on January 31. As shown in figure 4-4, the CLW increased from about 1930 to 2400 as the wind shifted to the north and northeast and increased in speed after 2215. The strong flow from the north-northeast apparently forced the moist air upslope and produced the abundant CLW over the Mogollon Rim. The decrease of CLW from 0000 to 0300 during even stronger upslope flow, was apparently due to less available water in the atmosphere as evidenced by lower levels of water vapor detected by the microwave radiometer. Precipitation rates at Happy Jack also decreased from 0000 to 0300; the lower CLW was not due to greater conversion to snowfall. As can be seen in figure 7-1, there was a break in the cloud tops as seen both by the satellite and the radar.

The first precipitation was observed at Happy Jack from 1900 to 2000 as the cloud deck thickened. The mean rate from 1900 to 0300 was 1 mm h^{-1} with a peak of 2.3 mm h^{-1} coinciding with the wind shift between 2000 and 2100. Thus, while CLW was abundant, snowfall was rather light; this suggests the storm was inefficient in converting liquid water to ice particles prior to 0300. The mean vertically integrated CLW from 2000 to 0300 was 0.32 mm. Assuming most of the CLW was in the lower atmosphere, the mean windspeed during the period was about 15 m s^{-1}, yielding a CLW flux of 4800 g s^{-1} per 1 m crosswind distance. If that amount was converted to uniform precipitation over the 25-km crosswind distance of the barrier above the 2.1-km contour, a rate of 0.7 mm h^{-1} would result, which is similar to the rate observed at Happy Jack located on the downwind side of the barrier. Roughly as much water was crossing the Mogollon Rim unconverted to snowfall as was falling upon it; that is, the storm was approximately 50 percent efficient during this period.

The wind shifted abruptly from north-northeasterly at 0300, to southwesterly by 0330, to southerly by 0430, and then back to northerly at 0500. This shift occurred throughout the 600-m layer immediately above ground as observed by the acoustic sounder; this shift was also confirmed by the Happy Jack tower wind vane. Windspeeds fell to less than 7 m s^{-1} by 0330 and were less than 5 m s^{-1} from 0400 to 0600. Cloud tops decreased rapidly from 0300 to 0510 after which radar data were lost for a time due to a power failure (see gaps in figs. 4-4 and 7-1). The CLW (now entirely SLW) also decreased sharply, and the snowfall rate jumped to 3 to 5 mm h^{-1} from 0300 to 0600. Whatever the cause of the abrupt change, most of the storm's snowfall fell during this 3-hour period at Happy Jack.

The SLW was limited from 0500 to 0830 after which it increased again. Snowfall rates did not exceed 0.4 mm h^{-1} for the rest of the storm after 0600 and averaged less than 0.2 mm h^{-1} from 0600 to 1700.

7.3.4 Aircraft Mission of January 31, 1987. - Winds above Happy Jack were northerly from 0600 to 1700 on January 31. Speeds varied with height much more than before and also varied with time. While speeds were near 9 m s^{-1} throughout the 100- to 600-m a.g.l. layer at 0600, speeds increased from 6 m s^{-1} at 100 m to 16 m s^{-1} at 500 m by 0700. The speed shear with height continued for the rest of the storm. The 300-m speeds were near 8 m s^{-1} from 0800 to 1330 and then quickly increased to 12 m s^{-1} and eventually exceeded 15 m s^{-1} by 1700. The second SLW maximum of the storm took place from 1200 to 1500, coinciding with an increase in cloud thickness and water vapor. However, the water vapor decreased for several hours after 1400; and this "drying out" of the atmosphere marked the end of the storm period.

The second aircraft mission took place during a period of moderate CLW (radiometer hourly means near 0.2 mm) shortly before the second CLW maximum, which peaked near 0.6 mm. The King Air aircraft took off from the Prescott airport at 0916 and proceeded eastward toward the Happy Jack region. The aircraft climbed to 5.3 km on route. No SLW was detected on the climbout sounding with the exception of a very thin layer near 3.5 km. Some weak layers of ice particle cloud were observed. The equivalent potential temperature generally increased slowly with height from 308.5 degrees K at 2.0 km to 310.5 degrees K at 4.0 km indicating a slightly stable atmosphere. However, essentially neutral stability existed from about 3.3 to 4.5 km.

The wind direction veered with height from northwesterly near the surface (1.6 km) to north-northwesterly near 2.7 km to north-northeasterly from about 3.1 to 4.3 km. Winds were northerly at higher altitudes. Windspeeds increased with height from approximately 13 m s^{-1} at 2.0 km to 20 m s^{-1} at 4.0 km.

At the beginning of the mission, a layer cloud, consisting entirely of ice crystals, was over the region with a base near 4.6 km over the Happy Jack area. However, a sounding made to 5.2 km near the end of the flight did not detect the upper deck.

The first significant SLW cloud was encountered at 4.1 km near 0932 while descending toward Happy Jack. Peak SLW amounts recorded by the King instrument were 0.5 g m^{-3} (0.3 g m^{-3} with the Johnson-Williams instrument, which was unreliable after 0943) with most readings in the 0.1 to 0.3 g m^{-3} range. The IPC averaged less than 0.1 L^{-1} in the upper portion of the cloud deck; and crystals appeared to be compact, possibly rimed, and less than 0.5 mm in diameter. The first sharp increase in IPC was briefly observed at 3.4 km (-8.0 °C) with a peak concentration exceeding 30 L^{-1}. A second similar peak was at 3.2 km (-7.0 °C), but mean concentrations remained low. Columns and needles predominated in the high IPC zones with a lower background of compact particles, possibly small graupel. The latter rarely exceeded 1 mm in diameter.

Upon reaching Happy Jack at the lowest permissible altitude, just below 3.0 km, the aircraft headed northward at that level into the wind. The IPC at that altitude, where the temperature was near - 6 °C, varied considerably from totally ice-free regions to peaks exceeding 40 L^{-1}. Most crystals appeared to be small needles and columns from the 2D-C images, with occasional graupel-like particles near 0.5 mm in diameter. However, the mean IPC value was only 3.6 L^{-1} for the 11 minutes the aircraft remained near 2.97 km. The SLW amounts were near 0.15 g m^{-3} in the Happy Jack vicinity but increased farther upwind. Amounts consistently exceeded 0.5 g m^{-3} from 21 to 26 km north of Happy Jack near the upwind slope of the barrier with a peak value of 0.7 g m^{-3}. By this time, the aircraft's climb performance had noticeably deteriorated due to airframe icing; it was decided to turn south and climb out of the cloud deck. The IPC decreased dramatically above about 3.0 km. The cloud top was reached at 3.85 km where the temperature was -9.5 °C. The aircraft stayed above cloud from 0955 to 1018 to sublimate its load of ice while flying north-south over the Happy Jack area. Essentially no ice crystals were observed during this period showing that the upper level deck was not acting as a "seeder cloud" for the lower deck.

It was not possible to stay in the lower cloud deck for extended periods because of unusually heavy airframe icing. Consequently, the normal horizontal passes were not flown. Rather, the aircraft would descend at about 400 m min^{-1} to the lowest flight altitude of 2.97 km, approximately over Happy Jack, and immediately climb back up above the deck. This procedure was followed three times from 1018 to 1057 after which the aircraft returned to base.

Each of the three decent/ascent passes observed a similar condition. Cloud top was uniform near 3.82 km with a temperature of about -9 °C. A shallow stable layer (inversion) existed just above the cloud deck. The atmosphere was slightly stable from 2.97 km, the lowest level sampled, to about 3.5 km and neutral above.

The IPC was typically less than 0.05 L^{-1} from cloud top to almost the lowest level sampled. The images were compact, probably small graupel, with few particles larger than 0.5 mm. However, in each of the three cases, markedly higher IPC was encountered below about 3.0 km where the temperature was -5.5 °C. Peak concentrations below 3.0 km were 5 to 15 L^{-1} with means of only a few per liter. Apparently, columns and needles were being formed, possibly by the Hallett-Mossop mechanism as the temperature criteria were satisfied and some apparently small graupel were present.

Cloud droplet spectra were examined at various times and altitudes. Values of TD were typically 14 to 19 μm near cloud top and 18 to 22 μm in the rest of the cloud. Droplet concentrations were usually in the 25 to 50 per cm^3 range according to the FSSP. However, the FSSP appeared to underestimate concentrations during this field season. Figure 7-2 shows an example of the cloud droplet spectra, in this case near 3.0 km

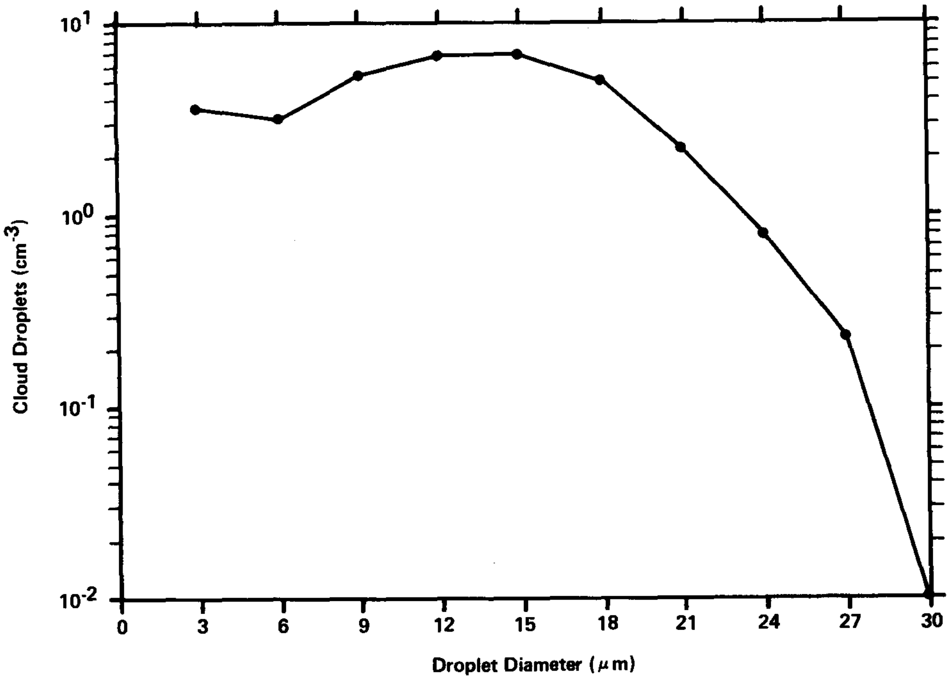


Figure 7-2. - FSSP cloud droplet spectra near 3.0 km altitude over Happy Jack at 1037 on January 31, 1987. The number of droplets were measured for each 3-μm size bin.

measured about 1037 over Happy Jack. The spectra shown was typical of this mission but broader than most observed during the field season.

The highest IPC's observed below 3.0 km were possibly due to the very low concentrations of graupel-like crystals falling from above into warmer cloud layers with few large droplets. If so, the Hallett-Mossop criteria may have occasionally been satisfied so low concentrations of needles or columns could form; but the ice enhancement was quite limited. At any rate, resulting precipitation was very light. The rate was near 0.1 mm h^{-1} at the Happy Jack high-resolution gauge during the aircraft mission. Similarly, trace amounts were recorded at the Flagstaff airport.

The King instrument SLW observations for all passes in the Happy Jack vicinity were averaged for approximately 200-m intervals (between 2.97, 3.2, 3.6, and 3.82 km) and partitioned according to direction from Happy Jack (north, south, east, west). The few level passes at 2.97 km were also averaged for various distances from Happy Jack. No distinct pattern emerged, probably due to temporal variations. Zones with little or no SLW were occasionally encountered between 3.2 and 3.6 km in all directions from Happy Jack. The lowest layer means, including all directions, were 0.08 g m^{-3} for 3.2 to 3.4 km and 0.13 g m^{-3} for 3.4 to 3.6 km. However, individual passes through these layers exceeded the layer means for 3.6 to 3.82 km (0.18 g m^{-3}) and 2.97 to 3.2 km (0.20 g m^{-3}). The highest SLW observed was 0.60 to 0.70 g m^{-3} from 20 to 26 km north of Happy Jack at 2.97 km. This was the closest measurement to the upwind slope of the barrier, and the high SLW content was apparently produced by strong orographic lift in that region.

It was anticipated that SLW amounts might be less south of Happy Jack than to the north due to downslope subsidence; this was not observed and suggested limited downslope motion within approximately 20 km south of Happy Jack where measurements were made. This situation was likely because of the limited terrain gradient in that region.

The flux of SLW flowing over the barrier was calculated for the cloud layer above 2.97 km. Mean SLW values were used for all observations in the previously noted 200-m layers together with mean windspeeds for the same four layers. The mean wind increased with height from 9.5 m s^{-1} near 3.1 km to 13.4 m s^{-1} near 3.7 km. Wind directions were near 10 degrees. The flux for each sublayer, for a 1-m crosswind width, was simply the layer depth multiplied by the mean windspeed and SLW content; this yielded the flux in g s^{-1}. The total flux for the 2.97- to 3.82-km cloud depth was 1456 g s^{-1}. A more realistic figure would have included liquid cloud below the lowest aircraft sampling layer. The only SLW observation in that layer was from an icing rate meter on a 30-m tower at 2.38 km. The meter did not detect any SLW during the aircraft mission. Assuming a linear distribution of SLW with height (with zero at 2.38 km), in the absence of other observations, yielded a mean of 0.10 g m^{-3} for the 2.38- to 2.97-km layer. The mean windspeed in the layer was approximately 7 m s^{-1} according to the acoustic sounder. The resulting SLW flux below the aircraft was thus estimated at 413 g s^{-1} for a total flux over the barrier of 1870 g s^{-1}.

Another approach to estimation of SLW flux over the Mogollon Rim barrier is to use the microwave radiometer observations as discussed in section 5. This approach has the advantage of providing continuous vertically integrated measurements from the surface (at Happy Jack) to cloud top. However, since no information is provided on the vertical distribution of SLW, some assumption is necessary to decide the windspeed appropriate for calculation of the flux. In the case of the January 31 aircraft mission, the approximate SLW distribution is known above 2.97 km, but not below. With the assumptions made in estimating the SLW flux from aircraft and acoustic sounder observations, about 32 percent of the vertically integrated SLW would lie below 2.97 km. The mean speed from that level to cloud top was about 11.5 m s^{-1}; below that level the mean was near 7 m s^{-1}. Weighting the lower level by one-third for the estimated fraction of SLW yielded a mean windspeed of 10 m s^{-1} for the entire cloud layer above the radiometer. The SLW flux per 1 m crosswind distance was then the vertically integrated SLW multiplied by the mean windspeed with appropriate conversion to g s^{-1}. During the aircraft mission, the mean SLW from the radiometer was 0.2 mm, which yielded a flux of 2000 g s^{-1}. The excellent agreement with the estimate based on aircraft observations (1870 g s^{-1}) was very likely fortuitous considering sampling deficiencies and the assumptions made. However, it appears reasonable to assume that the SLW flux over the barrier was approximately 2000 g s^{-1} in the Happy Jack vicinity during the aircraft sampling period (0930 to 1100).

It is of interest to compare this value with other winter observations. Thompson and Super (1987) reported similar flux estimates over the Grand Mesa of Colorado. Values for nine storms sampled by aircraft ranged from 124 to 2707 g s^{-1}. Thompson and Super also presented estimates based on 3 months of radiometer sampling, which suggested that only about 10 percent of all hours with SLW present exceeded 2000 g s^{-1} on the Grand Mesa. Rauber and Grant (1987) provided a mean flux estimate of 2670 g s^{-1} for a 13-hour period with high liquid water content orographic cloud over the Tushar Mountains of Utah.

It appears that the January 31 period of aircraft observations over the Mogollon Rim had a flux of SLW comparable to relatively wet winter episodes over other barriers in the West. Some earlier and later portions of this storm were even wetter with more than twice as much SLW flux.

To put the flux values into better perspective, let it be assumed that all the flux could be converted into precipitation for elevations above 2.1 km. The crosswind extent of the barrier above that elevation was about 25 km for northerly winds. A SLW flux of 2000 g s^{-1}, per 1 m crosswind distance, converts to 1.8 x 10^5 m^3 h^{-1} (146 acre-ft h^{-1}) of water for the entire barrier. The area of the barrier above the 2.1-km contour was roughly 10^9 m^2 between Highway 87 on the south and Flagstaff on the north. The storm of January 30-31, 1987, produced SLW over a 24-hour period with a mean flux near 2000 g s^{-1} for a total near 4.3 x 10^6 m^3 h^{-1}. If precipitated uniformly over the 10^9 m^2 area, a water depth of 4.3 mm would result. Mean annual runoff from the barrier is approximately 110 mm per unit area. Thus, the estimated SLW flux from this single storm was equivalent to 4 percent of the mean annual runoff.

7.4 Aircraft Missions of March 15-16, 1987

7.4.1 Overview. - The last major storm of the 1987 field season was a Pacific polar cold front that developed a wave and then a major low after reaching the California coast. The front wrapped around the south side of the developing low and preceded it across Arizona. After the passage of the trailing low across the state, the moisture that had traveled around the north side of the low to the west side came across the state. Finally, as the storm passed away, the residual moisture developed into orographic convection confined to the high ground.

The aircraft flew twice on March 15 and twice on March 16. The first flight was among the frontal bands and is described in more detail below.

After the frontal bands had all passed, the character of the clouds changed. The satellite photographs showed the cloud bands to be broken or scattered convective rather than mostly stratiform; this reflected the typical cold air postfrontal instabilities with such storm systems. The 700-mb temperatures fell to about -10 °C. The clouds were closely associated with the center of the upper air low. This convective period lasted from about 1500 on March 15 to about 0900 on March 16. Liquid water values were light to moderate, precipitation also light to moderate, and cloud tops not excessively high. The cloud bases were low; supercooled fog was recorded at Happy Jack from 2400 to 0700 on March 16.

After 0900 on March 16, the radar indicated that the clouds became shallow and stratiform (the Payson time-lapse camera showed fog all day) with traces of cirriform clouds high overhead. Eventually, a thick high cloud connected with the lower layers to produce a heavier snowfall and reduced CLW. These clouds were basically a stratiform band that had wrapped around the back side of the low. The tallest band, at about 1800, marked a trough passage during which the upper winds shifted from northwesterly to northerly. The graph of CLW shifted from a spiky nature, suggestive of stratocumulus, to a semismooth graph with coarser variations, suggestive of an orographic stratus cloud. In fact, Happy Jack was in supercooled fog from 1900 on March 16 to 0600 on March 17, as indicated by the tower-mounted icing rate sensor. Radar cloud tops were moderate to 2400 and then shallow or nondetectable. The stratiform CLW ended about 0630 on March 17.

The details of the second flight on March 16 are not presented here. The convective end of the episode on March 17 was not examined by the aircraft. Figure 4-9 can be referenced to help understand the case studies in the context of the entire storm.

7.4.2 First Aircraft Mission of March 15, 1987. - During the first aircraft mission, the clouds being examined were those ahead of a cold front. Prior to the storm, the clouds were very high cirrus with temperatures about -50 °C. As seen in figure 4-9, these high clouds ended at about 0900 in the Happy Jack region, in agreement with the radar echoes.

A band of clouds, visible in the time-height diagram of the radar echoes from about 0615 to 0815, was also seen as a prefrontal band in the satellite photographs. The band was just one of many originating near the southwest border of Arizona. The set of bands at that time nearly covered the entire state and were merged into each other; they climbed in height from their origin to the southwest and peaked in the center of the state. Subsidence apparently created clearing to the northeast of the Mogollon Rim.

The aircraft took off at 0717 and made a sounding to 5.3 km on route to the Happy Jack area. The ceiling at Prescott was only about 300 m with an overcast sky and light rain. The atmosphere was neutral up to about 3.4 km and slightly stable to the top of the lower cloud deck near 5 km (-17 °C). Some thin scattered clouds existed at higher levels. Very little SLW was observed on the climbout sounding, and precipitation-sized particles were abundant. Winds were within about 10 of 210 degrees true at all levels. Speeds were approximately 20 m s^{-1} from 2.0 to 3.4 km and increased to 30 m s^{-1} by 5.0 km.

The aircraft made its descent passes over Happy Jack in the northern rear portions of one of the bands mentioned above. A series of parallel-to-the-wind passes were made from 0735 to 0900 starting at 5.29 km and stepping down to 3.00 km. Headings were near 35 or 215 degrees. The cloud deck was initially much thicker over the Happy Jack region than farther west as the sun was completely obscured at 5.29 km, the highest sampling level where the temperature was -20 °C. No SLW was detected at 5.29 or 4.37 km, and the IPC frequently exceeded 15 L^{-1}. In general, the aircraft found light snowfall of about 7 L^{-1} and an estimated 0.15 mm h^{-1} precipitation rate. Vertical air velocities were positive at perhaps 1.0 m s^{-1} (estimating that the zeroing error was about 0.5) upwind of the crest and -0.5 m s^{-1} downwind at all levels examined by the aircraft.

The mean IPC was calculated for the same area used in section 6 (a rectangle 15 km north-south by 10 km east-west with Happy Jack centered on the east-west axis but 5 km from the southern edge) for each pass corresponding to the highest terrain. At 5.29 km, the mean was 4 L^{-1}. Most ice particles were less than 0.5 mm and irregular in shape at the highest sampled level. By 4.37 km (-14 °C), dendritic shapes were becoming common in addition to irregulars; and some evidence of aggregation was present. A significant fraction of the ice particle population exceeded 1.0 mm; the mean IPC was 8 L^{-1}.

Estimated trajectories of those particles contributing to the precipitation rate suggested that the particles were probably already large and falling from more than 20 km upwind of the barrier. Those particles that fell through the SLW below happened to receive an additional boost in mass, size, and terminal velocity.

Significant liquid water contents were found only on the lowest passes and within about 7 km of the crest. That may be a timing coincidence because the radiometer also observed increased liquid water during the low aircraft passes. The radar indicated that there was a break between the prefrontal bands at that time.

The first SLW was encountered at 3.75 km, along a 9-km zone directly over the highest terrain, beginning almost over Happy Jack on the south. The SLW was presumably due to orographic uplift as moist air was forced upward over the Mogollon Rim. However, Johnson-Williams instrument amounts were only 0.01 to 0.05 g m^{-3}. While peak IPC exceeded 10 L^{-1}; the mean was 7 L^{-1}. Dendrites and aggregates (of dendrites) were common, often larger than a few millimeters. The next pass at 3.33 km only encountered trace amounts of SLW, again over the higher terrain. Ice particle characteristics were similar to the 3.75-km level.

Three passes were then made at 3.00 km (-6 °C), each of which observed a continuous zone of SLW located from over Happy Jack to about 10 km north. The SLW amounts in that region were occasionally greater than 0.10 g m^{-3}, and mean IPC was near 6 L^{-1} with peaks two or three times higher. Many particles exceeded 1 mm, and some were a few millimeters or more in size. These large particles were usually aggregates. Some graupel-like snow and columns or needles also existed, generally less than 1 mm in size. The TD was calculated for the SLW zone at 3.00 km and was found to be about 14 μm. Droplet concentrations averaged 40 to 50 per cm^3. The lack of large (> 24-μm diameter) droplets would not be conducive to ice multiplication by the Hallett-Mossop mechanism.

Two more passes were made at 3.00 km, but perpendicular to the wind between 0900 and 0930; one passed over Happy Jack and the other 15 km farther north (downwind). Limited amounts of SLW existed over the windward slope and top of the Mogollon Rim, seldom in excess of 0.10 g m^{-3}. Mean IPC was near 5 L^{-1} over the Mogollon Rim.

Much higher concentrations, however, with several IPC peaks greater than 50 L^{-1} were then observed west of the higher terrain; this was probably associated with the approach of a thicker cloud deck of the next band. Cloud tops over Happy Jack reached a minimum of 5.9 km at 0820 and then continually increased to the end of the mission reaching 8.0 km by 1045. Hourly precipitation amounts also increased from near zero prior to 0800, to 0.7 mm from 0800 to 0900, to 2.2 mm from 0900 to 1000, to 3.6 mm from 1000 to 1100.

The next major band started to pass over Happy Jack at about 0820 and lasted to the frontal passage at about 1300. The aircraft examined the arrival of the band over Happy Jack and returned for a series of ascent passes in midpassage. This cloud band was more prominent in the satellite photographs than most others. When the visible pictures became available well after sunrise, the band had a triangular shape with a narrow south-southwesterly origin much like severe thunderstorms in the Plains States but not having such prominent contouring in the infrared satellite photographs. This band, the rear of which coincided with the cold front, also terminated in the subsidence zone beyond the Mogollon Rim. The satellite photographs suggest that this band was dynamically well organized, ingesting tropical air at the band's origin at the northern end of the Gulf of California, slowly raising the moist air to approximately the center of the state, and then dropping precipitation as the band moved.

Even though the measured south-southwesterly winds aloft were approximately parallel to the axis of this cloud band, the band itself propagated eastward. The aircraft examined only the downwind end of this band;

it was like examining the anvil outflow of a thunderstorm about 300 km downwind of the main updrafts. The IPC was typically 20 L^{-1}, and the estimated precipitation rates were about 1 mm h^{-1}. The Camp Verde sounding and radar observations indicated a cloud top temperature near -40 °C. The vertical air velocity appeared positive (zeroing error unknown) and did not exhibit a change in direction as the air passed over the high ground. The liquid water amounts were as in the previous band during the initial passes. But when the aircraft returned in the middle of the band, these amounts were much smaller on the lowest pass and essentially zero at higher levels. It appears that the heavier rate of precipitation utilized all available SLW.

Between 0930 and 1000, three passes were made in the 2.85- to 3.01-km layer over the southern-facing portion of the Mogollon Rim about 40 km south-southeast of Happy Jack. SLW was consistently present above the windward slope and top of the Mogollon Rim with peak amounts greater than 0.1 g m^{-3}. However, peak IPC frequently exceeded 15 L^{-1}. As the aircraft flew over the west end of that area (due south of Happy Jack), IPC exceeded 50 L^{-1}.

A second series of along-the-wind passes was made over Happy Jack from 1005 to 1045 at altitudes from 3.00 to 4.36 km. By this time, the IPC had increased to mean values between 12 and 42 L^{-1} in the Happy Jack region. Peak values frequently exceeded 50 L^{-1}. Examination of the 2D-C images at the lowest level (-6 °C) revealed frequent needles and some graupel-like snow, both generally less than 1 mm maximum dimension. However, most of the snow mass was clearly in the form of aggregates from a few to several millimeters across. At the highest sampled level of 4.36 km, ice particles tended to be smaller presumably because of less aggregation. More individual particles were apparent and were primarily irregular rather than dendritic in shape; the latter might be anticipated because of the -15 °C temperature at that altitude. As the aircraft left the Happy Jack area at 1045 and climbed toward the west, similar concentrations of smaller (< 1 mm) irregular particles were seen at temperatures near -21 °C. It appears that ice was forming high in the cloud deck by this time (1050). As noted previously, radar cloud tops had increased to about to 8.0 km.

Some transient and limited amounts of SLW were observed over the highest terrain at the 3.00- and 3.32-km levels, presumably due to orographic uplift. Liquid water was essentially nil at higher levels. It appeared that the storm over the Happy Jack region was very efficient by this time, converting all available SLW to snowfall.

During the first band, the ice particle habits were mostly single particles aloft developing appendages in the dendritic growth zone, becoming graupel-like in the -10 to -8 °C region, and finally producing a few aggregates on the lowest passes to dominate the precipitation rate there. The second band was different. Almost all of the particles contributing to the much greater precipitation rate were aggregates and graupel. Particle sizes were much larger in the second band. Perhaps the greater vigor of the second band generated more water in southwestern Arizona through stronger updrafts and accounted for the graupel and larger ice water content. The -40 °C tops would allow for very large concentrations of ice particles to be generated in any remaining SLW.

The aircraft flight track, examined in a frame of reference drifting with the air, showed that the aircraft examined one air parcel three times over a half-hour period at the start of the second band. The three passes, all at the lowest flight level, were upwind, over, and downwind of Happy Jack. The ice particle characteristics were examined to see of there were any significant changes in character of the ice particle population as the air passed over the barrier; none were found--neither the size nor habit spectrum changed very much. The concentration doubled, and the precipitation rate stayed about the same. The biggest particles were generally found on the upwind side and presumably fell out rapidly. The smaller particles peaked slightly in size over the barrier.

The radiometer observed SLW (surface temperature was below 0 °C during this entire storm) also changed during the mission. Liquid was first detected at 0600 and reached a peak of 0.41 mm at 0645 still prior to aircraft takeoff and a second peak of 0.27 mm at 0845 during the first series of aircraft passes over Happy Jack. By the second series (1000 to 1045), the mean value was 0.08 mm with a peak slightly greater than 0.1 mm. Presumably, most of the limited SLW during the second series was below the lowest aircraft sampling level and was therefore warmer than -6 °C. The nucleating ability of AgI is very limited at such warm temperatures although dry ice seeding could be employed. In view of the limited and warm SLW available and high IPC, seeding potential was likely very limited or nonexistent during the later portion of this mission. However, some potential may have existed during the first series of aircraft passes over Happy Jack when SLW existed up to the -10 °C level and mean IPC was only about 5 L^{-1}.

In general, the data indicated that the storm was generating its precipitation far to the southwest of Happy Jack, outside the operational area. The ice particles were simply settling through the air at Happy Jack, and their encounter with any SLW over the crest was only an added bonus to their growth. The SLW seen by the aircraft was only an orographic component that was independent of the main storm dynamics. The storm organization and energy came mostly from the synoptic scale as the front moved over the project area.

In both bands, the SLW appeared to have been produced orographically in the lower cloud layers independent of the band dynamics. The first band had steady amounts of SLW in the lowest layers as observed by both the aircraft and the radiometer. The SLW was apparently not being totally consumed by the ice particles falling through it. Only the leading and trailing edges of the second band had similar amounts of SLW observed by either system; the center of the band had only about 0.06 mm observed by the radiometer and trace amounts by the aircraft. The peaks in the radiometer values occurred between the cloud bands where there was less likelihood of falling snow consuming the SLW.

It appears that a proper seeding strategy for such a cloud system would be to continuously try to seed the lower cloud layers with an exotic mixture of AgI capable of nucleating significant ice near -6 °C. This strategy may have helped in the first band and would have done no harm in the second. The treatment should have been beneficial to the larger SLW amounts in between the bands. Dry ice treatment would also have been appropriate for such temperatures, especially between bands. Perhaps radar could have been used to guide a seeding aircraft to the airspace between bands where there would be greatest benefit from seeding.

The rapid change of conditions with time observed on this flight was characteristic of several other aircraft missions. The conceptual steady-state orographic storm with a shallow cloud deck existing for many hours was rarely observed during the 1987 Arizona field program.

7.4.3 Second Aircraft Mission of March 15, 1987. - Takeoff was at 1415 on the second aircraft sampling mission on March 15. The atmosphere was generally neutral with winds near 235 degrees and

20 m s^{-1} at 3 km, backing to near 200 degrees, and about 25 m s^{-1} in the 4.3- to 5.3-km layer. Liquid cloud was observed only between 4.4 and 4.7 km on the climbout sounding, but ice particle cloud existed up to 5.3 km, the highest level sampled, where the temperature was -23 °C. Radar tops over Happy Jack were almost 8 km at the time where the temperature was about -45 °C.

A series of along-the-wind passes was made over Happy Jack between 1430 and 1525 from 5.31 to 3.04 km. Liquid water was almost nonexistent at all levels. The radiometer CLW averaged about 0.05 mm during the period in general agreement with the low and spotty aircraft SLW measurements. The IPC, averaged over the first 10 km downwind of Happy Jack, was as high as 43 L^{-1} at 4.39 km, but decreased as the aircraft descended until only 1 L^{-1} existed at 3.04 km. A second pass at that (lowest) level near 1520 detected no IPC where the aircraft was below cloud base. However, as the aircraft was descending in its series of stepped passes, a large hole in the cloud deck was moving over the Happy Jack vicinity. Satellite imagery showed a number of holes in the cloud deck that covered much of Arizona as the clouds were changing to a regime of general small convection. Snowfall at Happy Jack, which had been 4 mm h^{-1} from 1400 to 1500, was essentially zero from 1500 to 1700. No radar returns of SLW were observed between 1525 and 1600.

The aircraft proceeded to make a series of VFR crosswind passes southwest of Happy Jack to detect SF_6 being released (see sec. 9.5.4). A second series of five crosswind SF_6 sampling passes was made directly over Happy Jack starting at 1610 (3.03 km), gradually climbing to 3.32 km, and returning to 3.03 km for the final pass near 1640. By then, microwave radiometer values were peaking near 0.25 mm; and radar tops were only about 4 km (with a separate higher deck). SLW was observed on each pass with peak values of 0.1 to 0.2 g m^{-3} but with frequent gaps that had no SLW. The IPC was quite low from 0.1 to 0.4 L^{-1}.

Three final along-the-wind passes were made over Happy Jack from 1655 to 1720. The first and highest pass at 4.41 km detected no liquid cloud and only 4 L^{-1} mean IPC. However, over 0.3 g m^{-3} SLW was detected about 40 km south of Happy Jack near the end of the pass. This liquid water was in an approaching cloud band with tops near 5 km that had earlier produced graupel (reported by the person at the SF_6 release site). The system may have been interesting but was not sampled further because of aircraft weather radar warnings and pilot fatigue (> 7 hours IFR flight that day).

The two final passes at 3.77 and 3.03 km, respectively, detected spotty SLW with peak amounts near 0.1 g m^{-3}. The IPC averaged 7 L^{-1} at the upper level but only 0.1 L^{-1} at the lower level. The cloud layer was poorly organized.

As did the earlier mission on this day, this flight illustrated the rapid changes in cloud conditions with time observed on several of the Arizona aircraft missions. The first series of passes encountered a deep cloud system with cold tops, abundant ice particles, and very little liquid water. The weather modification potential of this system was nonexistent. A hole in the cloud deck (postfrontal clearing) moved over Happy Jack followed by a shallow deck with modest SLW but virtually no ice. The shallow deck may have been suitable for precipitation augmentation. After less than an hour of these apparently favorable conditions, the cloud deck over Happy Jack became disorganized. However, as the mission was ending, a more organized line was approaching from the south that had abundant SLW and that had produced graupel. Hourly mean CLW of 0.3 mm was observed between 1800 and 1900, soon after the mission.

Obviously, cloud seeding potential rapidly ranged between none and promising. Probably the only reasonable seeding strategy on a day like March 15 would have been to continuously seed with the assumption that periods with abundant ice particles and little or no SLW would not be adversely affected to any significant degree. Such an assumption is reasonable based on present evidence and understanding (e.g., Super, 1986), but this assumption should be tested further. It would be very difficult or impractical to respond to the short periods of apparently seedable conditions with anything but continuous seeding. It is noteworthy that the ground-released SF_6 reached significant altitudes during this mission (see sec. 9.5.4).

7.4.4 Aircraft Mission of March 16, 1987. - A short mission was flown during mid-morning of March 16. Takeoff was at 0930 at which time Happy Jack snowfall was decreasing from earlier hourly amounts near 2 to less than 1 mm h^{-1}. Precipitation ended shortly after 1000 as radar returns essentially disappeared. The radar tops had been near 5 km at 0800 and 3.7 km at 0930.

The climbout sounding showed a slight increase in equivalent potential temperature with height; but for all practical purposes, the atmosphere was neutral from the surface to 5.3 km--the highest altitude attained. The wind veered from westerly below 3 km to northwesterly above, and speeds were approximately 5 m s^{-1} at 3 km, 10 m s^{-1} at 4 km, and 5 m s^{-1} at 5 km.

Four passes were made along northwesterly or southeasterly headings over Happy Jack from 4.37 to 3.02 km altitude. The temperature was -20 °C at the highest level and -11 °C at the lowest. The tops of higher convective elements were penetrated at all levels. The convection was weak and poorly organized for the most part. A few turrets had rather firm tops, and Johnson-Williams instrument SLW amounts occasionally exceeded 0.4 g m^{-3}. However, most of the clouds were ragged, with peak SLW near 0.05 to 0.15 g m^{-3} and peak IPC of 10 to 20 L^{-1}.

The several turrets with the firmest tops were selected from the video record of the forwardlooking camera. The TD, mean FSSP concentration, and Johnson-Williams instrument SLW content were similar for all these penetrations, regardless of altitude. TD was usually between 16.0 and 18.5 μm, concentrations from 6 to 20 per cm^3, and mean SLW from 0.03 to 0.07 g m^{-3}. The clouds were obviously weak with few, small droplets. No attempt was made to do a life-time study of any individual turret so it is not known whether cell life times were sufficient for some weather modification potential to have existed. Certainly, some of the firmer turrets were almost ice free. However, the general impression from viewing the video tape was of very weak and ragged convection raising out of a general layer. Holes were often seen in the cloud layer. Most turrets penetrated already had abundant natural ice. It seems most likely that seedability was essentially nonexistent at that time. The mean radiometer CLW during the mission was 0.05 mm and quite variable with time as characteristic of convection cells moving overhead. Peak values were only 0.15 mm, again suggesting weak convection.

7.5 Summary of Case Studies

Measurements from several instrumentation systems were jointly examined for a few selected 1987 storm periods. Data sources included several aircraft sensors, radar, acoustic sounder, radiometer, precipitation gauges, satellite photographs of cloud cover, and standard weather maps. These intensive case studies revealed a number of interesting features not necessarily apparent from less in-depth analysis.

The mission of January 28, 1987, was in an orographic wave cloud produced by strong winds and associated uplift over the Mogollon Rim. The cloud quickly evaporated downwind of the Mogollon Rim in subsiding air. The cloud was almost free of ice crystals except in the lower, warmer portion where needles and occasional small graupel were found satisfying the criteria for some Hallett-Mossop multiplication of ice crystals. While SLW amounts were light to moderate in this cloud, the strong winds resulted in an appreciable SLW flux. Seeding with AgI should have produced snowfall from this relatively uncomplicated cloud, but simple calculations show the snow would likely have fallen predominately downwind of the Verde River drainage because of the high cloud base and strong winds. Nevertheless, clouds of this type are excellent candidates for physical seeding experiments.

The storm of January 30-31, 1987, produced considerable SLW over almost 24 hours. Two aircraft missions were flown, the first of which illustrated the rapid changes that often occur in Arizona winter clouds making it difficult to obtain representative measurements with aircraft. The second mission was flown during a period of moderate CLW in an almost ice-free orographic cloud produced by upslope flow from the north-northwest. Evidence of limited ice multiplication by the Hallett-Mossop process was again found in the lower, warmer cloud region. Heavy air frame icing limited in-cloud sampling time, but enough observations were made to indicate this cloud system likely had considerable cloud seeding potential. The CLW flux from this single 1-day storm was estimated as equivalent to 4 percent of the mean annual runoff from the area.

Four missions were flown during the storm of March 15-16, 1987, and illustrated the band structure that was common to several Arizona storms and that resulted in rapid changes in cloud conditions (and seedability) with time. In general, the ice particles leading to snowfall on the Mogollon Rim first formed high in the bands a considerable distance upwind. When CLW was formed at low levels over the Mogollon Rim due to orographic uplift, the settling ice particles grew rapidly and resulted in heavier snowfall on the Mogollon Rim than elsewhere. Larger amounts of CLW existed between the bands because fewer ice particles were available to consume the liquid water. While much of this storm likely had very limited or no seedability due to high natural efficiency, seeding may have increased the snowfall during some periods. The rapid changes in cloud conditions suggest that it would have been very challenging to attempt to seed only those times when nature was inefficient. Continuous seeding would probably have been necessary assuming that the seeding would have no significant effect during naturally efficient periods; there is evidence from other locations to suggest this is true, but studies should be conducted in Arizona to test the assumption there.

8. SEEDING POTENTIAL OF MESOSCALE CONVECTIVE EPISODES

Three general storm periods were classified as MC cases by the classification scheme described in section 4. These periods had localized convective activity that occurred in the absence of any major synoptic scale forcing. The field observational program, particularly the aircraft standardized flight procedure used, was principally designed for data collection during more widespread storm situations. Therefore, the data sets collected during the isolated convective situations are somewhat incomplete in that repeated passes (life cycle studies) were not usually made through individual convective cells. However, all available data for the localized convective periods were examined in an attempt to estimate their seeding potential. The results are summarized below.

8.1 Mesoscale Convective Episodes of February 9-12, 1987

During this 3-day period, CLW was recorded by the radiometer on a nearly continuous basis with significant peaks during the daytime hours. Synoptically, a series of minor short-wave troughs brought clouds and moisture to the area; but these were weak and did not produce well-organized storm systems. Instead, a generally unstable air mass was present throughout the period; and scattered showers developed partially in response to daytime heating although there were some suggestions of amplification due to weak synoptic scale features. Radar data were unavailable for the entire period due to a component failure. Although conditions were seemingly quite static, significant cloud microphysical differences were observed from day to day. Therefore, each day is discussed separately.

8.1.1 February 9, 1987. - At approximately 2100, the radiometer first indicated CLW, which persisted for the remainder of the day with maximums approaching 0.20 mm. No precipitation was recorded in any of the gauges during this period, and no aircraft observations were made. No definitive conclusions regarding seedability were possible although the presence of CLW in the absence of any recorded precipitation may have been indicative of potential.

8.1.2 February 10, 1987. - Weak CLW values were present at the start of the day. Hourly average amounts rose gradually throughout the morning and early afternoon hours reaching values over 0.3 mm between 1300 and 1500. Activity slowly diminished after this time, then abruptly fell to zero shortly after 1700. The radiometer CLW record largely consisted of numerous short-duration abrupt changes or "spikes" indicative of convective elements passing overhead. The highest of these spikes was in excess of 1.0 mm at about 1130.

An aircraft mission was conducted between 1000 and 1213. Multiple layers of generally broken cumuliform cloud were investigated. The strongest observed showers were associated with a band of clouds having the highest tops within the area. The summit of this band was composed of visibly glaciated, weak cumuliform elements. This feature was penetrated at multiple levels as it advected across the Happy Jack area in moderate southwesterly flow. The highest elements reached approximately 5.1 km where the temperature was approximately -14 °C; more typical tops were about 4.3 km and -8 °C. Cloud bases were near 3.0 km where temperatures were slightly below 0 °C.

The majority of cloud penetrations at all sampling levels displayed high natural ice concentrations. Crystal concentrations averaged over the entire length of each in-cloud pass were predominately in the 10 to 50 L^{-1} range. Liquid water measurements were limited during the flight due to instrument failures. The limited data available showed only small amounts of liquid available during penetrations. Thus, for the period of aircraft observations, it appears that nature was quite efficient and that little if any seeding potential was present. Due to the lack of FSSP data to provide cloud droplet spectra, the possibility of an operative Hallett-Mossop type ice multiplication process cannot be addressed.

Small amounts of precipitation were recorded at six of the seven gauge sites. Almost all of this occurred between the hours of 0900 and 1400. Slightly more precipitation fell before noon than after. The maximum hourly amount recorded was 1 mm of water equivalent at Happy Jack. The gauge records indicated precipitation periods were brief and intermittent from the convective shower activity. The fact that most precipitation occurred prior to the time of maximum surface heating is suggestive of a minor synoptic scale impulse acting as a trigger. This fact is also consistent with the observed passage of a higher cloud band during the aircraft mission.

Inspection of satellite photographs indicated quite uniform cloud conditions throughout the period during which CLW was observed by the radiometer. The cloud cover consisted of a broken stratocumulus deck with some higher towering elements. Flagstaff NWS surface weather observations substantiated this interpretation.

To summarize, the radiometer record showed a protracted period during which many short-duration spikes of liquid were present. These spikes were consistent with the presence of convective elements such as those observed during the aircraft mission. However, the aircraft data indicated natural ice production (even at warm temperatures) of sufficient magnitude to efficiently utilize the bulk of the liquid water being produced. It appears that little, if any, seeding potential existed during this day.

8.1.3 February 11, 1987. - A broken stratocumulus cloud deck was present over the area during the early morning hours. No synoptic forcing features were forecast, but adequate low-level moisture was available to suggest that surface heating would produce towering cumulus of sufficient size to generate widely scattered showers. This activity was expected to peak during the mid- to late afternoon hours. Weak CLW amounts were observed during the nighttime hours until about 1100 as the thin stratocumulus advected over Happy Jack. Towering cumulus subsequently started developing; and by slightly after 1300, CLW spikes in excess of 1.0 mm were being observed although no virga or rainshowers were visible from Happy Jack. This period of heightened activity persisted until about 1430 when values abruptly fell to near zero levels, and only occasional spikes rose to approximately 0.15 mm. The reason for this sudden and unexpected change was not obvious.

An aircraft mission was conducted from 1417 until 1558, which unfortunately was just after the fall in peak CLW activity at the radiometer site. A broken stratocumulus cloud deck, with bases near 3.0 km at -1 °C temperature, was present over the area. Out of this deck rose very widely spaced towering cumulus clouds. Spacing between these elements was estimated to be on the order of 10 to 20 km. The towers grew rapidly, had moderate liquid water content in their updraft cores (several penetrations indicated values in the range 0.25 to 0.45 g m^{-3}), and relatively little natural ice development at most levels in the younger clouds. The cloud droplet spectra measured by the FSSP indicated insufficient concentrations of large droplets to support a Hallett-Mossop ice multiplication process. Cloud tops grew quite quickly to about 5.2 km (about -15 °C) and then rapidly glaciated. Maximum tops reached an estimated 5.6 km. The cloud lifetimes appeared quite limited. Individual elements appeared to rapidly grow, glaciate at the tops, develop graupel, and then subside. Precipitation shafts were observed at the bases.

Satellite photographs substantiated the presence of scattered towering elements rising from a lower deck throughout the period. Surface weather observations at Flagstaff and precipitation gauge network records suggested that the duration, and perhaps the amount, of activity was greater to the north and east of the research area than near Happy Jack. Flagstaff reported towering cumulus clouds and rainshowers of unknown intensity predominately to the northeast of the station from 1400 through 1800. Towering cumulus in all quadrants and light rainshowers at the station were reported at 1900 and 2000. Flagstaff precipitation totals for these hours were 0.5 mm and 0.25 mm, respectively. Only two of the seven network precipitation gauges recorded precipitation during the day. The Happy Jack gauge indicated hourly totals of 0.05 and 0.1 mm at 1300 and 1400, respectively, while Mormon Lake received similar small amounts each hour from 1600 through 2100. Obviously, precipitation was very light and widely scattered.

The short cloud lifetimes, wide spacing between potentially seedable cloud entities, natural cloud top glaciation, and the very small and highly localized precipitation amounts observed all argue that little significant increase in area-wide precipitation could be achieved through seeding on this day.

8.1.4 February 12, 1987. - During the nighttime hours, CLW was intermittently recorded. One strong spike, in excess of 1.0 mm, occurred at about 0500; and small amounts of precipitation were recorded at three of the gauge sites. Morning visual observations indicated the presence of a broken stratocumulus deck over the area with a cirrus layer above. Happy Jack observers reported trace amounts of precipitation occurring at 0800. Once again, no synoptic scale features were anticipated; and the morning weather forecast indicated that the best possibility of significant convective showers would be mid-afternoon in response to local heating. An altocumulus band crossed the area during mid-morning producing measurable amounts of precipitation at six of the seven gauge sites. This feature was probably associated with passage of a minor upper air disturbance. This system produced the majority of the precipitation recorded during the day. By 1200, the mid-level deck had moved to the east; and cumulus and towering cumulus started to build. Some virga was observed.

An aircraft mission was conducted between 1311 and 1428. A scattered cumulus deck was present with bases approximately 3.0 km and -1.5 °C. Maximum observed tops were about 4.1 km where the temperature was -8 °C. The clouds were almost entirely ice free, which was not surprising considering their warm temperatures. The cloud droplet spectra were dominated by small sizes so that the Hallett-Mossop ice multiplication process should not have been operative. The higher elements investigated exhibited limited liquid water contents (0.2 to 0.3 g m^{-3}) particularly near their tops. Some seeding potential was indicated given the combination of available liquid water and lack of natural ice. However, the short lifetimes observed might preclude achieving cost-effective precipitation increases through seeding. Further investigation, including seeding trials, would be required to fully clarify the potential of similar cloud systems. Shortly after conclusion of the aircraft mission, convective activity rapidly declined and skies cleared by dark.

8.2 Mesoscale Convective Episode of March 10, 1987

The project weather forecast for the day indicated advection of a stable high-pressure ridge into the area. Upper winds were light, shifting from northwesterly near the surface to westerly at 500 mb. Nothing more than scattered fair-weather cumulus clouds were anticipated, and no precipitation was expected. Based on the forecast, normal ground operations were scheduled and the possibility of aircraft operations suspended.

A radiometer calibration was attempted from approximately 0930 until 1100. This effort was disrupted by the development of scattered cumulus clouds. Liquid water spikes to a maximum of 0.08 mm were observed when the data recording mode was resumed. Clouds continued to grow, and maximum CLW amounts in excess of 1.0 mm occurred between 1230 and 1430. Liquid values fell to zero after that time except for a brief period around 1600 when minor peaks to 0.1 mm were observed.

The Payson time-lapse data showed cumulus cloud development starting at about 1000. Clouds were initially somewhat towering and had bases far above the Mogollon Rim. Lifetimes were short--on the order of 15 to 20 minutes. By 1300, a stratocumulus deck had formed and intermittent rainshowers observed; these persisted until approximately 1520. Observable cloud tops during the showery period were fuzzy and indistinct indicating limited vertical motions and substantial glaciation. The cloud deck decreased after this time, and weak slightly towering cumulus were again apparent. Clearing occurred late in the afternoon. Radar data showed a maximum echo period between 1300 and 1430. During this time, cloud tops built to approximately 5.5 km; but reflectivity values were low. The radar returns abruptly ended at 1430 coincident with the observed start of cloud dissipation at the site.

At 1330, the Reclamation site coordinator arrived at Happy Jack, reviewed current conditions, and called for an immediate aircraft mission using a Reclamation electronics technician in Prescott as the flight scientist. The aircraft flew from 1428 to 1550, which was clearly after the peak in activity. The towering cumulus clouds that remained had high bases (around 3.7 km), little liquid water, low vertical velocities, uniformly high ice crystal contents, and short lifetimes. Areas of towering cloud were widely separated.

Traces of precipitation were recorded only at the Flagstaff Arboretum and Mingus Mountain gauges during the period.

It was concluded that some seeding potential was possibly present during the approximate 2-hour period when maximum liquid water peaks occurred. However, due to the widely scattered nature of the clouds and the apparent short lifetimes, the augmentation potential was considered negligible. It was unlikely that sufficient additional water could have been produced in a cost-effective manner through the application of any seeding technology.

8.3 Mesoscale Convective Episode of March 17, 1987

The forecast for the day called for ridging and drying with only a slight chance of convective showers. The morning Camp Verde sounding showed a generally stable and quite dry atmosphere with moderate northwesterly winds. Reports from Happy Jack indicated the presence of thin, low-level cumulus clouds moving rapidly overhead. No CLW was being observed at the time of the morning briefing.

The Payson time-lapse photographs showed that essentially fair-weather cumulus persisted throughout the day. Some of these cumulus were slightly towering, but lifetimes were generally less than about 15 minutes on those clouds that could be visually identified throughout their lifetimes.

Some weak radar echoes were observed starting at about 1100, but these echoes were very weak and base heights initially above 3.4 km. By about 1330, maximum radar bases and tops were about 2.7 and 4.3 km, respectively. Measurable precipitation fell only in the Baker Lake gauge between 1100 and 1600.

Based on the observed weak and poorly organized clouds, the project was terminated for the season and equipment dismantling started. It was felt that no worthwhile seeding potential existed during this episode.

8.4 General Conclusions

The investigations of observed MC cases lead to the following general conclusions:

1. Episodes of this type were infrequent. A total of 5 days out of the 60-day field season were placed in this classification. This low frequency of occurrence in itself limited the potential for significant water resource enhancement through seeding efforts.

2. Surface, satellite, and aircraft observations indicated that potentially seedable cloud elements were often widely spaced and naturally produced only scattered small amounts of precipitation. The implication of this was that only a small fraction of the watershed area was covered by potentially treatable units, and even large precipitation increases through seeding individual clouds would probably have resulted in little area average precipitation.

3. Episode durations during which microphysical observations were available suggest periods of seeding potential were often brief. This limited window of opportunity is difficult to forecast and would present operational problems for effective treatment. In-cloud aircraft operations, for example, often require notification to the FAA 1-hour prior to takeoff.

4. Significant microphysical differences existed from day to day. Days with bands of cloud having relatively cold tops appeared quite efficient naturally although more cases would have to be investigated to confirm that this is the normal situation. Those cases that seemed promising for seeding were often comprised of shallow, warm clouds; but dry ice might well be suitable for starting the precipitation process in such clouds. However, the generally brief cloud lifetimes make it doubtful that significant seeding-induced precipitation would reach the ground.

All of these factors suggest that seeding MC cases offers little potential for significantly enhancing the water resources of the Mogollon Rim area during winter. It must be emphasized, however, that this conclusion is based on a very small sample obtained during a portion of a single winter. Further investigation of these occurrences is recommended. In any future efforts, standardized aircraft flight patterns should be modified to more effectively concentrate on obtaining detailed measurements throughout the lifetimes of single-cloud elements in the manner discussed by Isaac et al. (1982) or Cooper and Lawson (1984). This type of information could more precisely delineate whether seeding potential routinely exists.

9. EXPERIMENTS SIMULATING GROUND-BASED SEEDING

9.1 Design of Experiments

One of the goals of the 1987 field program was to assess the practicability of ground-based cloud seeding with AgI without actually releasing any seeding material. The experimental design called for ground releases of pure SF_6 (sulfur hexafluoride) gas from points upwind of the Mogollon Rim. The gas was then to be detected downwind of the release site during cross-wind passes by the University of Wyoming King Air aircraft, whose normal complement of instruments was supplemented by a continuous gas analyzer. The SF_6 plume cross sections would then be analyzed to determine concentrations and horizontal and vertical spreading of the SF_6 at a number of downwind distances. These measurements could be compared with models resulting from air pollution research to see if such models might be applicable to the more complex terrain of the Mogollon Rim.

Eight field experiments with SF_6 were conducted with releases from five sites for the dates, times, and conditions listed in table 9-1. Some experiments were conducted under nonstorm conditions, which permitted aircraft flights close to the surface. Other experiments were conducted with the aircraft sampling in cloudy and snowy conditions, more closely representing potential AgI seeding periods.

The SF_6 releases were usually begun prior to the beginning of a flight in order to allow a quasi-steady-state plume to develop downwind. Exceptions were for flights in which the objective was changed from cloud physics to tracer detection during the mission. The SF_6 release rate was controlled with a flowmeter. Also, the SF_6 cylinders were weighed before and after each release period to determine the mean rates of release.

The aircraft usually flew a series of passes approximately perpendicular to the wind direction and at several altitudes to identify the horizontal and vertical plume structure. Such series were made at one to three different downwind distances on each mission.

9.2 Description of Equipment and Calibrations

The continuous SF_6 analyzer utilized on board the King Air aircraft was designed by Washington State University (Benner and Lamb, 1985) and manufactured by Scientech in Pullman, Washington. The analyzer was mounted in a rack along with cylinders of ultrapure nitrogen and hydrogen, both necessary to operate the analyzer. An external pump was used to draw in ambient air through a port located in the top right section of the fuselage through about 3 m of Teflon tubing. The air was then injected into the inlet port of the analyzer. The lag time through this tubing was measured on the ground by releasing an excess flow of 95 ppt (parts per trillion) calibration gas into the port on the outside of the aircraft. The lag time between injection and response was measured to be about 3 seconds. The response time of the analyzer itself has been shown to be about 0.4 second (Benner and Lamb, 1985).

Table 9-1. - The locations, dates, times, and surface conditions for the SF_6 tracer experiments.

Site	Latitude Longitude	Elevation (m)	Location
1. Cherry Road	34°34'15" 112°04'16"	1524	Cherry Road, Forest Road 372A, 5.9 km north of Arizona Highway 169
2. Yavapai Road	34°29'06" 111°36'59"	1844	East of Camp Verde: Yavapai County Road 9 and Forest Road 9c
3. Forest Road	34°21'52" 111°23'01"	1650	Southeast of Pine: Forest Road 64, 4.8 km east of Arizona Highway 87
4. Mingus Road	34°42'31" 112°08'51"	2142	Mingus Mountain Road: intersection of Arizona Highway 89A and Forest Road 104
5. Payson Airport	34°15'24" 111°20'20"	1572	Payson Airport

Date	Release site	SF_6 release Times	Period (h)	Rate (kg h^{-1})	Surface temperature (°C)	Mean surface wind (deg)	(kn)	Flight times
1-30-87	1	0815 to 1145	3.5	22.2	6	180	3 to 5	0953 to 1236
2-3-87	2	1140 to 1550	4.2	21.6	10	190	20	1244 to 1646
2-15-87	2	1538 to 1815	2.6	25.5	6	180	10	1628 to 1908
3-2-87	3	1054 to 1218	1.4	24.0	7	190	4	1137 to 1301
3-5-87	5	1400 to 1622	2.4	24.8	17	180	4	1449 to 1734
3-9-87	4	1545 to 1810	2.4	24.3	12	190	10	1607 to 1836
3-15-87	2	1445 to 1640	1.9	23.0	1	210	10	1408 to 1742
3-16-87	4	1400 to 1615	2.2	24.2	-2	310	10	1412 to 1753

Pre- and postflight calibrations of the analyzer were performed for each tracer experiment flight. Six calibration gases of known concentrations (10.2, 95, 485, 972, 2902, and 4870 ppt) were injected into the analyzer while the output was recorded. The output was nearly linear over the entire range of calibration gases, with decreased output only for the highest concentration. Concentrations measured during the project were sufficiently calibrated by the first three test gases.

Initial calibrations suggested a relation of $C = 0.350 \times R$, where C is the SF_6 concentration in ppt and R is the instrument response in millivolts. The calibrations showed a lower response for the preflight tests and a higher for the postflight tests. The scatter of responses, using the logarithm of the instrument responses, had standard deviations appropriate to a factor of 1.62 at 10.2 ppt, 1.33 at 95 ppt, 1.17 at 485 ppt, 1.17 at 972 ppt, 1.11 at 2902 ppt, and 1.07 at 4870 ppt. When doing a linear fit to the lowest three concentrations of test gases, the slopes ranged from 0.30 for the postflight tests to 0.38 for the preflight tests. With such scatters in excess of 17 percent for the concentrations actually observed and the calibration actually changing during the flight, it is not appropriate to trust any refinements of the original calibrations.

It was reported by the contractor operating the SF_6 that the analyzer output varied with cabin pressure in the aircraft. A variation in the baseline was very obvious, but the cabin pressure was not recorded for comparison (the aircraft was pressurized). The drifting baseline, from whatever cause, had to be removed from the data in order to recover the plume profiles.

A graphical computer program was written to examine the raw data for each pass between nominated times, separated by as much as 200 seconds. From the linear graph, the analyst then nominated plume entry and exit times based on when there was the start or end of an obvious departure from baseline conditions. Least squares lines were then plotted, for visual reference only, through the baseline values on both sides of the plume. A line was then drawn from the baseline value at plume entry to the baseline value at plume exit. That line was subtracted from the raw data points to yield SF_6 concentration data corrected for a drifting baseline. Only such corrected data were used thereafter. Averages of other relevant parameters from the aircraft data system were made for the three zones of the nominated pass: before, inside, and after the plume to see if the plume position was related to temperature, winds, turbulence, or terrain.

9.3 Analysis Techniques

Direct detection experiments, such as these eight discussed here, provide the best data for indicating the behavior of plumes under real conditions; yet, they are time consuming, and flight conditions may limit the airspace available for the search of the plumes. Numerical models of plume behavior are more convenient, but simplifications and assumptions make their output of inferior quality to the real plume data. It is therefore appropriate to assess how well a model might describe a real plume; this is particularly important for complex terrain. Most air pollution models are constructed and calibrated for flat, level ground. While the Mogollon Rim might be approximated by smooth inclined planes, its approaches have hills and deep canyons to invalidate an assumption of flat and level.

For a ground-based plume source at the origin of a coordinate system, the downwind distance (x), the crosswind distance from the center line of the plume (y), and the height above the (flat) terrain of an observation (z), the Gaussian plume model (see Slade, 1968) can be written as:

$$C\,(x, y, z) = [Q/(\pi\, u\, \sigma_y\, \sigma_z)]\, \exp[-y^2/(2\, \sigma_y^2)]\, \exp[-z^2/(2\, \sigma_z^2)] \qquad (9\text{-}1)$$

where

C	= plume concentration
Q	= source strength
π	= pi, 3.14159
u	= average windspeed

σ_y^2 = variance of plume distribution in y
σ_z^2 = variance of plume distribution in z

While there are refinements available for the Gaussian model, it is a standard for comparison. The windspeed is usually increasing with altitude (z); but the model assumes it to be constant. The variances are both functions of downwind distance (x).

For constant altitude crosswind passes, the aircraft can measure the concentration profile directly with the SF_6 analyzer. For constants x and z, the logarithm of the Gaussian model is:

$$\ln(C) = -y^2/(2\,\sigma_y^2) + \text{constant} \qquad (9\text{-}2)$$

which is the equation for a parabola. Fitting the actual data to a parabola can yield an estimate of σ_y.

The SF_6 concentration data, corrected for baseline drift, were converted to logarithms. For concentrations less than 1 ppt, a zero was assigned as the logarithm. The logarithms were then fitted to a parabola using Chebyshev polynomials, which require data at equally spaced intervals perfectly supplied by the 1-second resolution provided by the aircraft data system. A graphic display then compared the actual data with the fitted parabola. For some of the actual plume profiles, the parabola was a close visual fit. Other data had concentration fluctuations within the plume or even gaps. In those cases, it was sometimes necessary to add to the data some extra zero values beyond the edges of the plume to force the parabola to zero outside the plume. The number of extra zeros needed was whatever number created the narrowest parabola. Too few would leave a broader parabola because the sides of the parabola would not efficiently be pulled down to zero. Too many would leave a broader parabola by making it fit numerous zero values far from the plume. Usually, only a few seconds worth of extra zeros, if any, were needed. The constants resulting from the fitting process were then solved for σ_y and for the peak of the parabola to give a plume concentration at $y = 0$. The average of the actual concentrations of SF_6 within the plume boundaries was also found.

Values for σ_y and downwind distances were calculated for all plume penetrations for all experiments. This data set was then trimmed. All passes more than 750 m a.g.l. (as measured by a radar altimeter) were eliminated from further consideration for the σ_y calculations. The radar limit was only a few meters higher, and the plume tops were usually weak and hard to define by 750 m a.g.l. All passes less than 6 km from the source were also eliminated because of difficulties in intercepting and obtaining representative profiles of the plumes at close ranges. Furthermore, all passes for which the peak in the parabola fit was less than 20 ppt (weak plumes) were eliminated. These restrictions excluded all passes for the plumes from Mingus Mountain on March 9 and 16. Such releases high in the air above a valley do not match a ground-hugging plume model.

The remaining values of σ_y (the horizontal dispersion coefficient) are plotted against distance from the release site in figure 9-1 (after figs. 3.10 and A.2 in Slade, 1968). The diagonal reference lines, A-F, are the Pasquill stability classes. It is seen that the scatter of points cover the entire range of possibilities. The scatter of general thermodynamic stabilities, as measured by temperature profiles of the actual atmospheres during the experiments, were usually about the neutral values. But as shown in the AgI tracer studies described by Holroyd et al. (1988), the ranges of microscale instabilities can be much greater because point

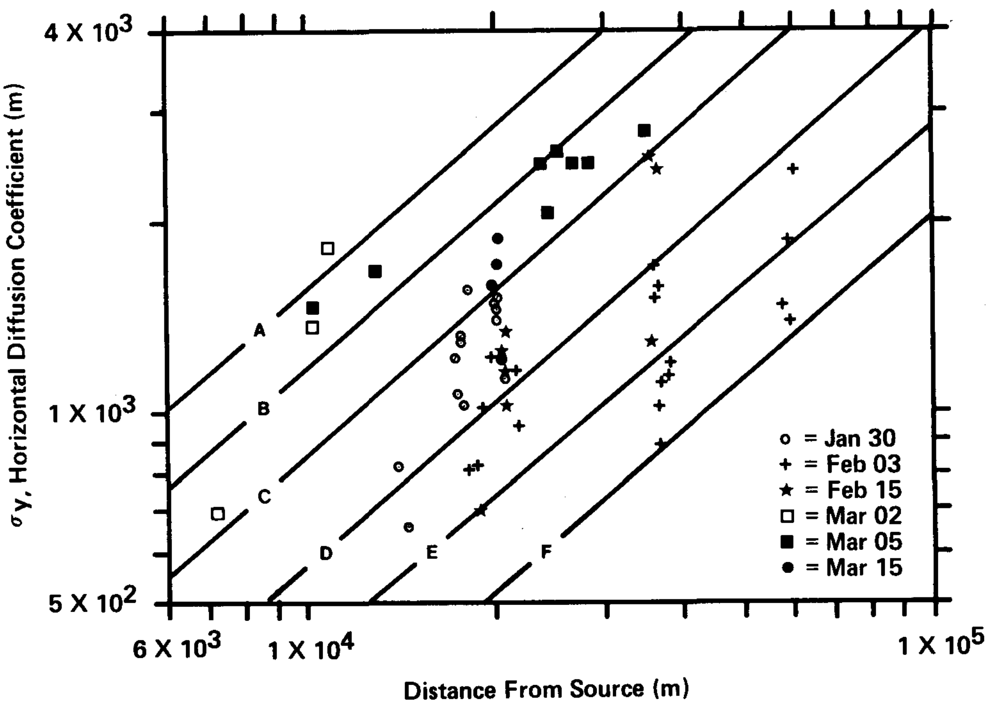


Figure 9-1. - Lateral diffusion (σ_y) versus downwind distance from the source for six tracer experiments. The diagonal lines are the Pasquill stability categories.

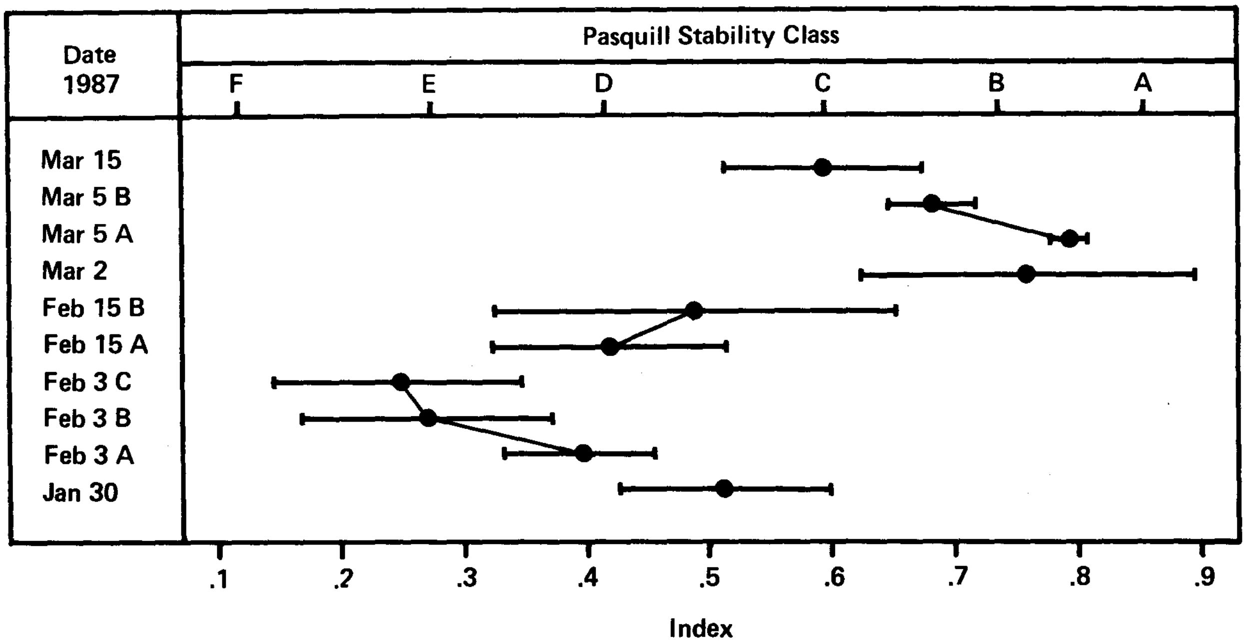
measurements of potential temperatures along a few-kilometer horizontal flight track can have a variance of several degrees. It seems that the range of lateral diffusion observations may be slightly excessive for what was thought to be the range of actual atmospheric stabilities. It is, however, apparent that the lateral plume behavior near the Mogollon Rim is comparable to behavior over flat terrain.

For each experimental date illustrated in figure 9-1, the data points tend to cluster around some stability class. In order to better identify that class, a relative index scale was created. The slopes of the diagonal lines in figure 9-1 average about 0.837. Using that slope, the intercept (expressed in logarithms, base 10) for a parallel line through every data point was calculated and then added to 1.0 to make the index a positive number. The mean and standard deviation of all such resulting index numbers were calculated separately for each series of downwind sampling passes during each experiment. The index numbers are plotted as points and "error bars" in figure 9-2 with the means connected for different downwind sampling distances from the release site on the same date. The approximate locations of the A-F Pasquill stability class lines are also given. This relative index makes a better assignment of each experimental day to the range of classes from slightly stable to moderately unstable.

The Gaussian dispersion model can also be solved for σ_z. For constant x and at y = 0 (plume centerline):

$$\ln(C) = -z^2/(2\,\sigma_z^2) + \text{constant} \tag{9-3}$$

Actual concentrations at y = 0 could fluctuate greatly so the concentration at the peak of the fitted parabola was selected as representative in order to have a value appropriate to smoothed data. Altitude values (z)



above the terrain were the averages from the aircraft radar altimeter over the width of the plume. When the aircraft terrain clearance exceeded the maximum range of the radar, a ground location in terms of pressure altitude was calculated for all the lower level passes and that ground location was subtracted from the pressure altitude of the higher level passes. High altitude and weak plumes were not excluded for the σ_x calculations as data points were limited. The Mingus Mountain releases were omitted from consideration because that of March 9 never interacted with the ground but rose as a twisting tube-shaped plume to higher altitudes; that of March 16 was inadequately sampled.

Using the square of the terrain clearance as the abscissa and the natural logarithm of the peak concentration as the ordinate, a linear least squares fit over a series of passes was determined. The coefficients of the resulting equations were then solved for σ_z (the vertical dispersion coefficient). Values of σ_z could even be calculated for conditions under which the aircraft was not allowed to approach the ground in the study area. Those values are plotted in figure 9-3 (after figs. 3.11 and A.3 in Slade, 1968). The points generally fell between the curves for slightly unstable (C) and neutral (D) in agreement with average temperature soundings. This indicated that the rise of the seeding plumes above the Mogollon Rim terrain was similar to the rise over flat and level terrain in the standard model.

9.4 Concentrations of Effective Ice Nuclei

Concentrations of ground-released tracers usually decrease with altitude; air temperatures also usually decrease with altitude. But the effectiveness of AgI for nucleating ice particles in supercooled clouds increases rapidly with decreasing temperature. The concentrations of ground-released AgI can therefore

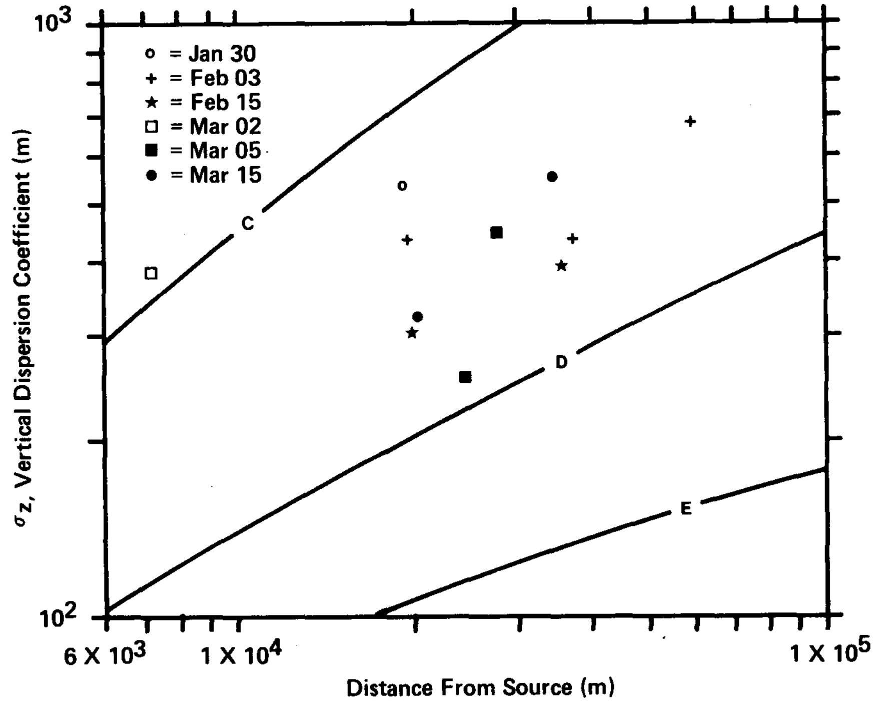


Figure 9-3. - Vertical diffusion coefficient (σ_z) versus downwind distance from the source for six tracer experiments. The diagonal lines are the Pasquill stability categories.

decrease very rapidly with altitude at the same time that its ice nucleus effectiveness increases with altitude. It is therefore not a simple matter to estimate the concentrations of effective ice nuclei within cloud.

The concentration (N) of effective ice nuclei at temperature (T) can be estimated from the SF_6 concentrations by:

$$N(T) = [S\ D\ E(T)\ r/R]\ \times\ 10^{-15} = [S\ D\ n(T)/R]\ \times\ 10^{-15}\ \text{nuclei L}^{-1} \qquad (9\text{-}4)$$

where

S = average SF_6 concentration across the plume, ppt
D = air density, kg m^{-3} (a function of altitude and temperature)
E(T) = ice nuclei effectiveness, nuclei g^{-1}
r = typical AgI release rate (30 g h^{-1} in this calculation)
n(T) = effective ice nuclei release rate, nuclei h^{-1}
R = SF_6 release rate, kg h^{-1}

S was directly averaged is this study. D was calculated for each pass from the pressure and temperature. R is known from the cylinder weighings.

Effectiveness curves for several AgI generators are given by Garvey (1975). It should be noted that these curves are based on cloud simulation chamber results and not on actual in-cloud measurements because the latter are not available. Therefore, the estimates to be calculated should eventually be checked against measurements from seeded clouds over the Mogollon Rim to test their validity.

The Montana State University generator was chosen because it was still in use in our recent experiments. The effectiveness for a AgI-NH_4I solution and 30 g h^{-1} release rate were combined into the effective ice nuclei release rate and fitted to an equation of the form:

$$\log_{10}(n) = d_0 + d_1T + d_2T^2 + d_3T^3 + d_4T^4 \text{ (nuclei h}^{-1}\text{)} \tag{9-5}$$

where the coefficients were found to be:

d_0 = 8.897462250
d_1 = $1.419118063 \times 10^{-1}$
d_2 = $1.916441581 \times 10^{-1}$
d_3 = $1.481453030 \times 10^{-2}$
d_4 = $3.261222769 \times 10^{-4}$

This polynomial is a precise fit at the following temperatures from Garvey (1975) for natural tunnel draft (light wind) conditions (those at -4 °C are estimated):

temperature, °C	-20	-16	-12	-8	-4
n, ice nuclei h^{-1}	2.4×10^{16}	2.4×10^{16}	9×10^{15}	6×10^{13}	3.4×10^{10}

Arizona conditions frequently appear too warm for normal AgI nuclei released from the ground. However, two other effectiveness curves were also considered. A recently developed remote-controlled generator described by Papania et al. (1986) uses a fan to better dilute the aerosol. Under the same test conditions and 30 g AgI h^{-1} burn rate for an AgI-NH_4I complex, that generator--built by Colorado International Corporation--has a higher effectiveness at warm temperatures but lower at cold.

The addition of chlorine atoms to the nuclei can give greater effectiveness at all temperatures (DeMott et al., 1983). Such exotic ice nuclei can be produced with the same generators noted above.

The effectiveness of any of the nuclei generators can be increased over "natural draft" conditions by the use of fans. The fan causes a rapid quenching and dilution of the aerosol and thereby reduces coagulation losses of the AgI aerosol. There are therefore several mechanisms for boosting the effectiveness and output of ground-based AgI generators for better nucleation at relatively warm temperatures.

Coefficients of equation (9-5) for the Colorado International Corporation generator and for a generator like that of Montana State University but using an exotic complex (with 30 mole percent NH_4ClO_4) are:

Colorado International Corporation	Exotic
d_0 = -7.703299106	-8.738916940
d_1 = -7.340187618	-7.639662550
d_2 = -8.450198003 x 10^{-1}	-8.558632061 x 10^{-1}
d_3 = -4.197688848 x 10^{-2}	-4.162624127 x 10^{-2}
d_4 = -7.549424998 x 10^{-4}	-7.370423989 x 10^{-4}

As in the case for the Montana State University generator, a value of 3.4 x 10^{10} nuclei h^{-1} was used as an estimate for -4 °C to force the fitted curve to low values. These coefficients were not precise fits to the effectiveness data at all temperatures, but the errors were of similar size to the scatter in the experimental data. At temperatures colder than -20 °C, these curves departed strongly from reasonable values so the -20 °C effectiveness values were used at such cold temperatures. The use of such coefficients in equation (9-5) enabled calculation of effective ice nuclei at temperatures between the experimental points by means of a smooth curve. In the discussion to follow, only the exotic curve was used for comparison with the Montana State University curve. The Colorado International Corporation curve was intermediate between the others at the temperatures of interest.

The vertical temperature profiles from rawinsondes released during storm conditions from Winslow, Arizona, and from Camp Verde, Arizona, from mid-January to mid-March 1987 were examined in terms of potential temperatures and equivalent potential temperatures. In an atmosphere with no cloudy air and of neutral stability, the potential temperature is constant with altitude; the potential temperature increases with altitude under stable conditions. In an atmosphere that is cloudy within the altitude band under consideration and of neutral stability, the equivalent potential temperature is constant with altitude. The cloudy atmosphere is convectively stable if equivalent potential temperature increases with altitude and convectively unstable if it decreases with altitude.

Figure 9-4 shows the range of temperatures actually found during Arizona storm conditions. The atmospheres were generally of neutral stability in terms of the equivalent potential temperatures. Ordinary air temperatures are indicated by the diagonal lines in the potential temperature graph. The following 700-mb temperatures were selected to represent the variety of storm conditions observed: +1 °C = warm (w), -5 °C = typical (t), -11 °C = cold (c), and -18 °C = extreme (e). More than 90 percent of the time the soundings were between the cold and warm curves. The extremely cold curve was for a series of soundings from only one general storm period (January 15-17, 1987).

In simulating a potential AgI ice nuclei plume, the actual SF_6 average concentrations (not parabolic fits or model predictions) were used to estimate the AgI concentrations. The actual temperature profiles during SF_6 measurements were adjusted by constant values (usually made colder) so that the 700-mb temperatures matched one of the four conditions listed above. The equation (9-4) for effective ice nucleus concentrations was then solved for each pass for the range of storm conditions. The results are discussed in the case studies.

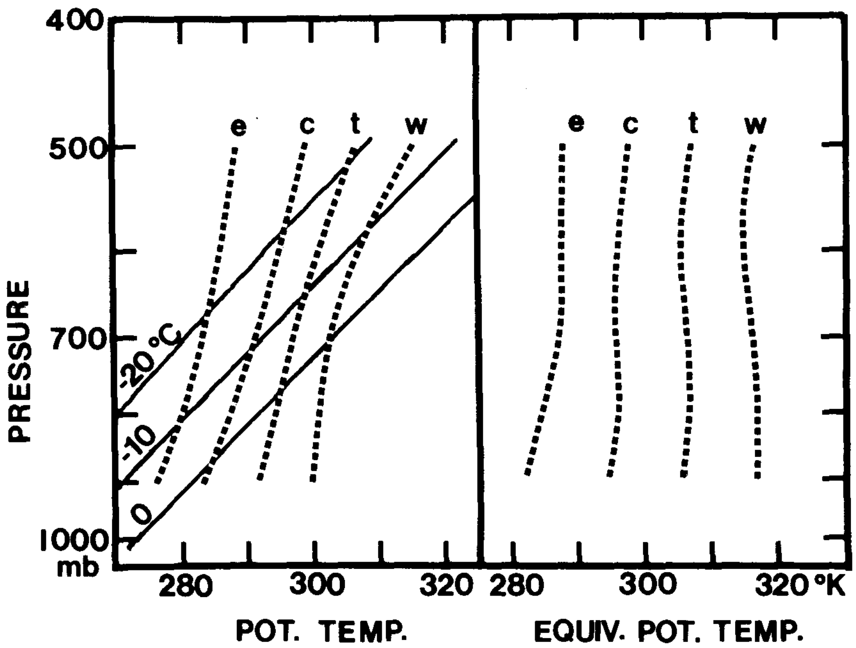


Figure 9-4. - The ranges of potential and equivalent potential temperatures observed during storm conditions from mid-January through mid-March 1987 based on soundings at Camp Verde and Winslow. The dotted lines are for soundings representative of warm (w), typical (t), cold (c), and extremely cold (e) storm conditions.

9.5 Individual Case Studies

The actual behavior of the SF_6 plumes was best illustrated in case studies. The Gaussian plume model coordinate system of equation (9-1) (x the downwind distance, y the crosswind distance, and z the height above terrain) formed a standardized basis for examining the plume behavior in the three mutually perpendicular planes. The figures to follow present the horizontal trajectories of the plumes (x-y plane) and the vertical cross sections along the plume length (x-z plane). The predicted concentrations of effective AgI ice nuclei for selected temperatures (x-z plane) are then shown assuming a Montana State University generator using a 30 g h^{-1} AgI consumption of an AgI-NH_4I complex. The vertical cross sections perpendicular to the plume axis at selected distances downwind (y-z plane) are then presented.

In order to smooth the irregularities in the plumes, the fitted parabolas were used to provide the concentrations that were contoured in the x-y and y-z figures. The average concentrations across the plume were contoured in the x-z figures. Aircraft pass locations are shown as boxes containing many flight tracks or as large dots. Contours away from those locations are only artistic smoothings. The 3-second delay in the detection of the SF_6 by the analyzer was always ignored as insignificant at the plotting scale used in the figures.

All experiments were done under skies with at least a cirrostratus overcast in order to minimize the effects of solar heating. Though the experiments are presented mostly in chronological order, the seventh is examined fourth so that the three experiments from the Yavapai Road site are considered together.

9.5.1 Cherry Road, January 30, 1987. - The first release of SF_6 was from the lowest site used. Following the winds in advance of an approaching storm, the plume went northwards over the Verde Valley, hugging the eastern slopes of Mingus Mountain but not climbing over any mountain barrier in the airspace examined. The temperature profile suggests that the plume would not have climbed above 2.8 km altitude due to an inversion. This first experiment was useful for testing operational procedures and for estimation of diffusion constants in a prestorm environment. However, the first experiment did not represent a flow regime in which the Cherry Road site would have been used to seed clouds over Happy Jack.

The plume was examined in a racetrack pattern by flying at the sides of Mingus Mountain and then sharply turning away when close. The plume was examined in only one general location as the aircraft made altitude steps upwards to near the top of the plume. The bottom of the plume was not determined and might have been elevated above the valley. The figures from this experiment are not presented.

The actual SF_6 average concentrations were converted to potential effective ice nucleus concentrations. At about the low 1.8 km m.s.l. altitude level, the concentrations showed a peak above 40 L^{-1} for the extremely cold conditions. While this appears to be a desired distribution, there are two points to keep in mind. The 700-mb level for rescaling the temperature was in the warm air above the inversion or stable layer; therefore, the rescaled temperatures were abnormally cold. Secondly, the low altitude of the plume was not a likely region for cloud formation, especially downwind from a ridge. So the indicated ice nucleus concentrations would have unlikely created a similar IPC.

9.5.2 Yavapai Road, February 3, 1987. - The first release of SF_6 from the Yavapai Road site resulted in one of the best plume definitions of the series of experiments. Though a storm was not present, the atmospheric structure was of neutral stability similar to typical storm conditions. The skies were of overcast cirrostratus with patches sufficiently thick to cast shadows on the ground. The plume passed just northwest of Happy Jack and was eventually tracked to 60 km downwind of the release site. Three vertical cross sections were made that gave dispersion constants in both the horizontal and vertical.

Figure 9-5A presents the horizontal positions of the plume. During the time the aircraft was sampling the plume near Happy Jack, the plume moved to the right looking downwind. The aircraft made an ascending series of passes and then a descending series at alternate altitudes; because of the plume movement, the two series were considered separately. The plume position is split in figure 9-5A in order to show the movement.

The vertical cross section of the plume along its axis is presented in figure 9-5B, where the middle series of passes were combined. A bimodal structure in the vertical appeared to be real. The broad lower band occupied a layer of neutral stability. The upper band was also in a layer of neutral stability but 0.2 °C warmer than the lower layer. The air rapidly became stable at the top of the upper maximum. From the time of the passes upwind of the crest to the passes downwind of the crest, the air warmed 1 °C.

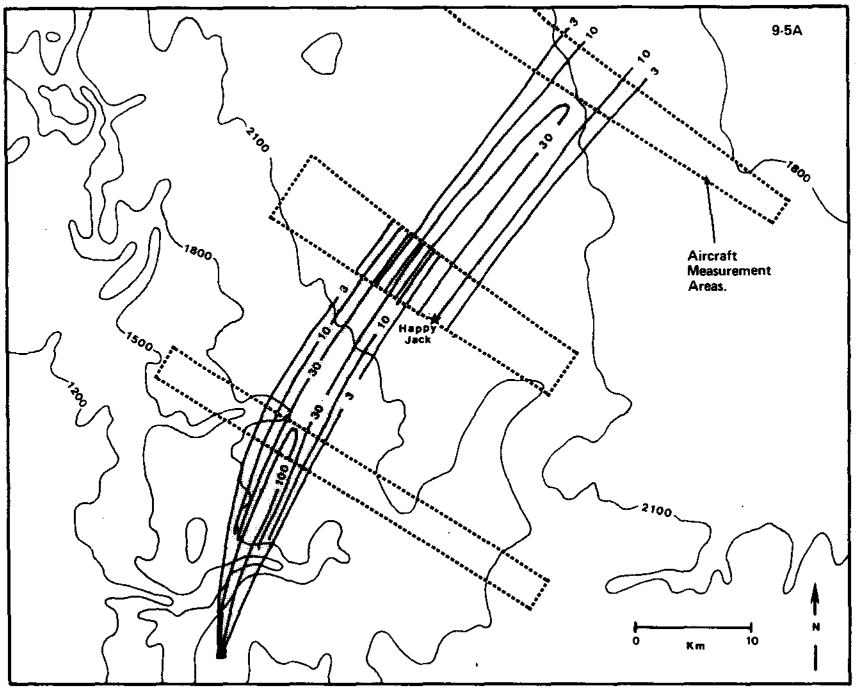


Figure 9-5A. - Horizontal structure of the SF_6 plume of February 3, 1987, as measured over three downwind areas. Concentrations are in ppt. Ground elevation contours are in meters above sea level. Aircraft sampling was done within the dashed areas.

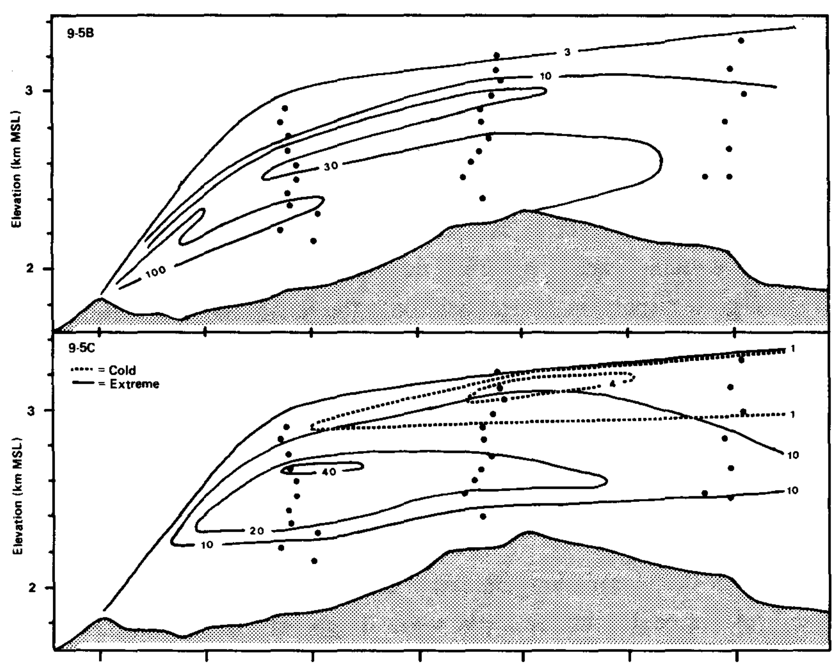


Figure 9-5B. - Vertical cross section of the SF_6 plume of February 3, 1987, along its centerline. Dots represent individual aircraft passes through the plume. Concentrations are in ppt.

Figure 9-5C. - Estimated AgI ice nucleus concentrations per liter corresponding to figure 9-5B for "cold" and "extremely cold" storm conditions (see text).

The actual SF_6 pass average concentrations were converted into potential effective ice nucleus concentrations in figure 9-5C for the extremely cold and the cold storm conditions. In the coldest case, the plume concentrations of ice nuclei exceed 20 L^{-1} for much of the region upwind of the crest with a peak of 40 L^{-1} over the foothills. Such a distribution was probably ideal in an actual cloud seeding situation and could tend to drop the nucleated snow near the crest. Concentrations of ice nuclei decrease downwind of the crest. The cold storm conditions, however, only produced a peak in excess of 4 L^{-1} over the crest. The lower half of the plume hardly produced anything. Any "snow" produced by the top of the simulated plume would likely fall beyond the crest in the drainage of the Little Colorado River.

The transverse vertical cross sections were well defined and are shown in figures 9-5D through 9-5G. The first series of passes over the foothills upwind of the crest revealed the plume structure details shown in figure 9-5D. The plume structure, as observed during the ascending series of passes over the crest (shown in fig. 9-5E), moved slightly to the right and broadened for the descending series shown in figure 9-5F. The plume structure could still be defined 60 km downwind of the release site as shown in the cross section of figure 9-5G.

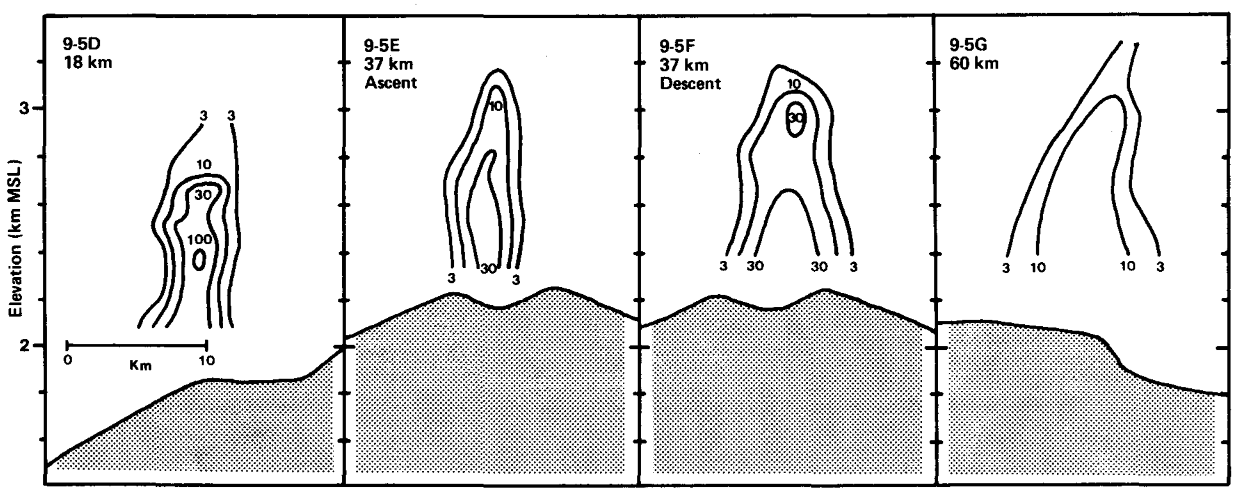


Figure 9-5D,E,F,G. - Vertical cross sections through the SF_6 plume of February 3, 1987, at indicated distances downwind of the source. Concentrations are in ppt.

9.5.3 Yavapai Road, February 15, 1987. - The second release of SF_6 from this site was measured at two downwind distances. The experiment was performed during a stratiform storm situation yielding light amounts of CLW and no precipitation. The plume passed just northwest of Happy Jack and was nearly straight, as shown in figure 9-6A. The plume's vertical cross section along its axis showed a rapidly climbing and then leveling plume that was bimodal in the vertical (figs. 9-6B and 9-6E) as the plume passed the crest. The upper maximum produced in excess of 30 L^{-1} of effective ice nuclei under the extremely cold conditions, with much of the plume exceeding 10 L^{-1} at altitudes higher than the crest (fig. 9-6C). The cold storms only produced a trace (0.1 L^{-1}) of active nuclei confined to the highest parts of the plume over the crest. In the y-z cross section over the foothills (fig. 9-6D), the plume was tall and straight with a tiny vertical extension at the top right. Over the crest (fig. 9-6E), the plume was distorted somewhat and bimodality was visible.

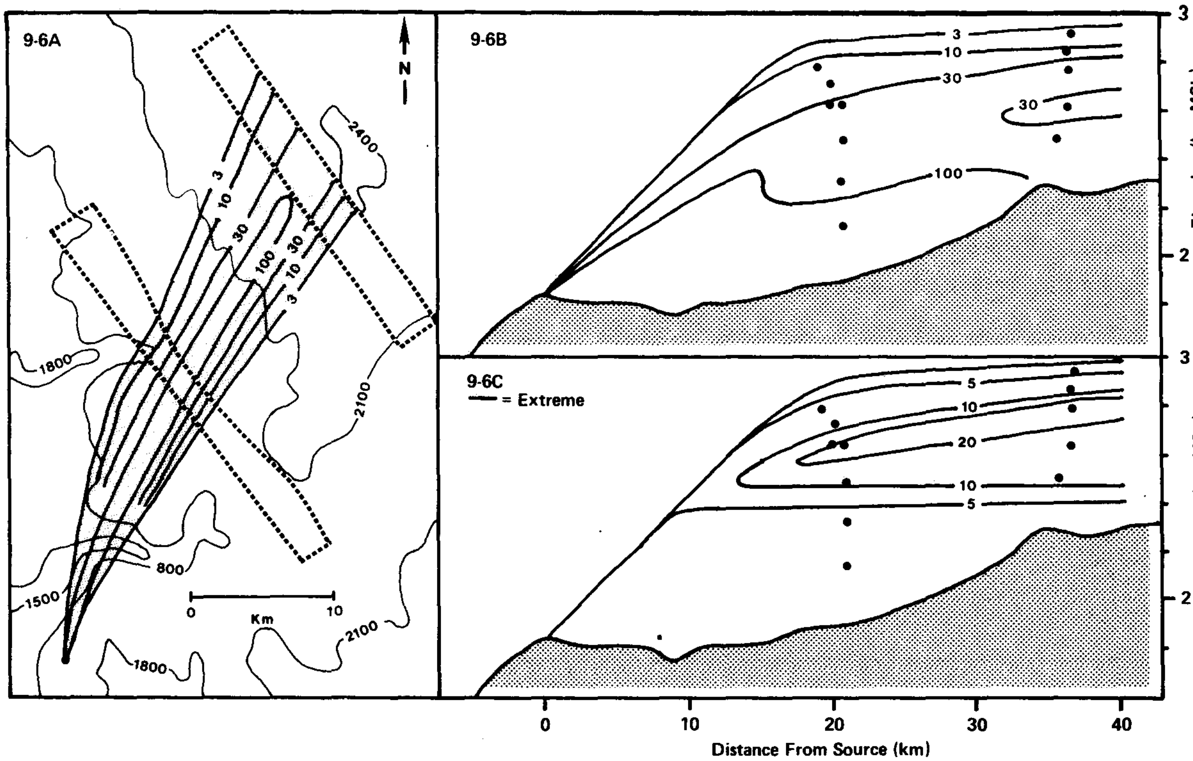


Figure 9-6A. - Horizontal structure of the SF_6 plume of February 15, 1987, as measured over two downwind areas. Concentrations are in ppt. Ground elevation contours are in meters above sea level. Aircraft sampling was done within the dashed areas.

Figure 9-6B. - Vertical cross section of the SF_6 plume of February 15, 1987, along its centerline. Dots represent individual aircraft passes through the plume. Concentrations are in ppt.

Figure 9-6C. - Estimated AgI ice nucleus concentrations per liter corresponding to figure 9-6B for "extremely cold" storm conditions.

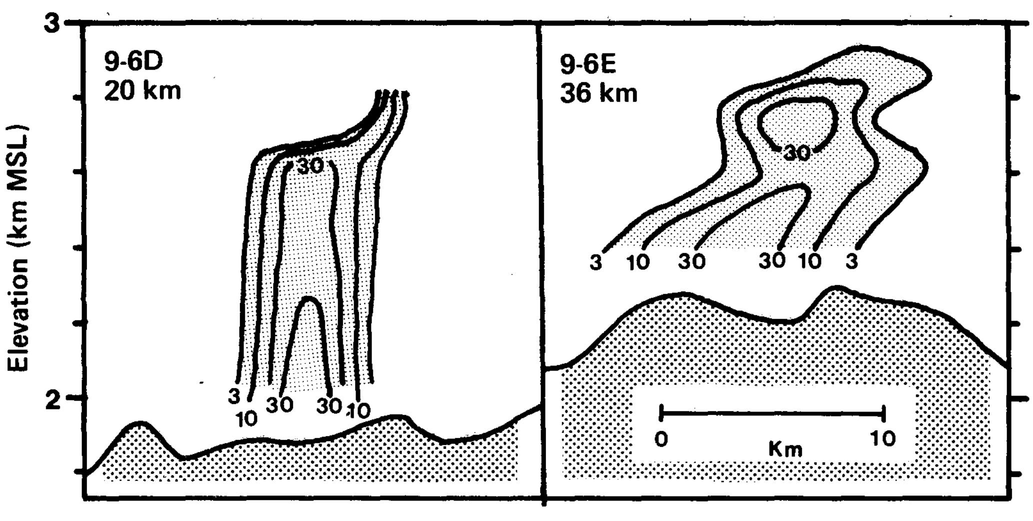


Figure 9-6D,E. - Vertical cross sections through the SF_6 plume of February 15, 1987, at indicated distances downwind of the source. Concentrations are in ppt.

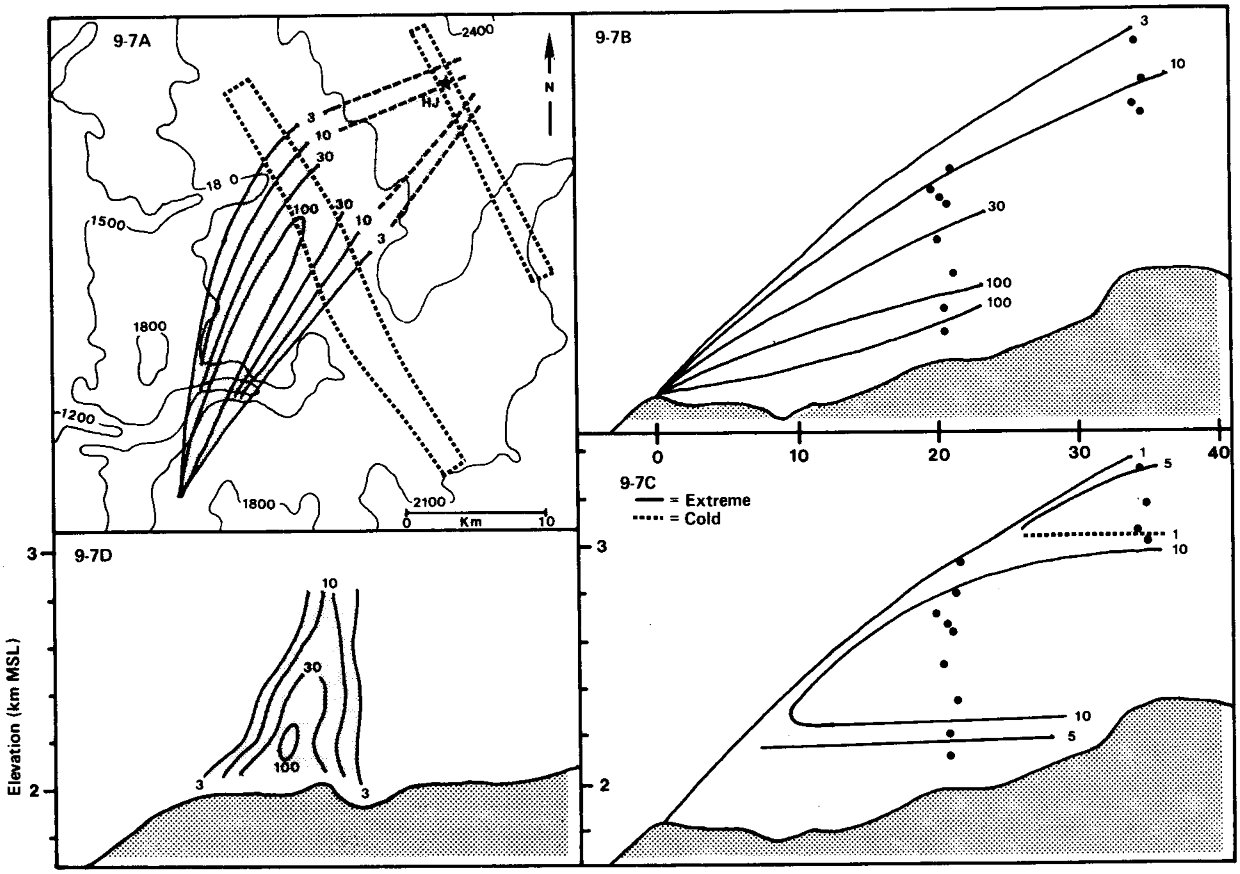


Figure 9-7A. - Horizontal structure of the SF_6 plume of March 15, 1987, as measured over two downwind areas. Concentrations are in ppt. Ground elevation contours are in meters above sea level.

Figure 9-7B. - Vertical cross section of the SF_6 plume of March 15, 1987, along its centerline. Dots represent individual aircraft passes through the plume. Concentrations are in ppt.

Figure 9-7D. - Vertical cross sections through the SF_6 plume of March 15, 1987, about 21 km downwind of the source. Concentrations are in ppt. The horizontal scale is the same as for figure 9-7A.

Figure 9-7C. - Estimated AgI ice nucleus concentrations per liter corresponding to figure 9-7B for "cold" and "extremely cold" storm conditions.

9.5.4 Yavapai Road, March 15, 1987. - In this experiment, the SF_6 was released into actual storm conditions and was eventually detected in regions of the cloud colder than 0 °C coexisting with falling snow. The storm structure had just changed after the frontal band passage to tall instability showers. The sampling, from 1538 to 1642, was actually done during a temporary lull in the storm as seen in the radar echo portion of figure 4-9. The vertical cross section in the foothills half way to Happy Jack was accomplished below cloud base. The plume passed exactly over Happy Jack; but at that location, the aircraft had to remain in cloud above a minimum terrain clearance and could not sample the lower parts of the plume. Figure 9-7A shows the horizontal trajectory of the plume, but the contouring at the downwind end only represented the top of the plume. This is seen more clearly in the vertical cross section along the plume axis in figure 9-7B. Potentially active ice nuclei, contoured in figure 9-7C, exceeded 10 L^{-1} in much of the plume for the extremely cold storm conditions. In the cold conditions, the top of the plume was marginally useful for snowfall enhancement at about 2 L^{-1} and was probably not much better in the lower regions over the crest that could not be sampled. The foothills vertical transverse section in figure 9-7D provided a good description of the plume in that location and was useful for both the horizontal and vertical dispersion coefficients. The vertical cross section over the crest, not shown, was sketchy and gave only an estimate of the vertical dispersion coefficient.

9.5.5 Yavapai Road Summary. - An examination of figures 9-5 to 9-7 shows similar plume structures in all cross sections even though the experiments represented nonstorm, stratiform, and convective storm conditions, respectively. However, the experiment shown on figure 9-7 was during a lull in the storm and may not actually represent embedded convection. This examination suggests that the experimental results may be of general applicability to at least stratiform clouds and perhaps weak convective clouds, though possibly underestimating vertical mixing in the latter. Furthermore, all three plumes passed near or over Happy Jack, indicating that the targeting strategy was appropriate and that the site could be routinely used as a seeding site for southwest winds.

The estimates of ice nucleus concentrations were sufficient for cloud seeding only under the extremely cold conditions with ordinary AgI nuclei. Under the cold storm conditions, the use of exotic AgI nuclei produced useful concentrations (not shown) but not at the typical or warm temperatures.

9.5.6 Forest Road, March 2, 1987. - The release of SF_6 from the Forest Road site was followed by a brief experiment at 1200. The flight crew had the impression that solar heating of the slopes of the Mogollon Rim was accentuating the vertical fluxes in excess of what would likely be encountered in stratiform storm conditions. The time-lapse photographs showed that the region was covered by a cirrostratus overcast that did not clear until after the flight. The illumination might have been declared "cloudy-bright." Furthermore, the Mogollon Rim was still covered with snow that was visible through the trees even in the side view of the time-lapse camera. The snow started to visibly melt only in the mid-afternoon and was gone from view at sunset. During the experiment, that much snow would have been a sufficient reflector of solar energy as to minimize its impact on the experiment. Even if the flight crew impressions were correct, this experiment is useful as an example of rapid lifting of the plume such as might occur with the MC storm classification where the clouds are generally confined to the high ground.

The plume traveled to the north-northwest, as seen in figure 9-8A, but was not tracked farther than the Mogollon Rim. The x-z profile of figure 9-8B shows that high concentrations of SF_6 did indeed rise rapidly to a high altitude above the Mogollon Rim. When converted into AgI ice nucleus concentrations (fig. 9-8C) for the extremely cold storm conditions, the plume produced a narrow zone of hundreds of particles per liter with most parts having in excess of 40 L^{-1}. Such high concentrations at that location could promote the rapid aggregation necessary to drop the resulting snow close to the Mogollon Rim rather than far into the downwind watershed. For the normal cold storms, the regular AgI produced up to 2 L^{-1} in the upper half of the plume and the exotic AgI over 10 L^{-1} in the middle of the plume; but such locations might result in snowfall downwind from the Mogollon Rim if there was an appreciable wind aloft. Finally, figure 9-8D shows that the SF_6 plume had a tall but otherwise normal appearance when crossing the Mogollon Rim. This profile enabled the derivation of both diffusion coefficients, which fell in the unstable parts of figures 9-1, 9-2, and 9-3 even though the temperature profile was of near-neutral stability below about 3.0 km

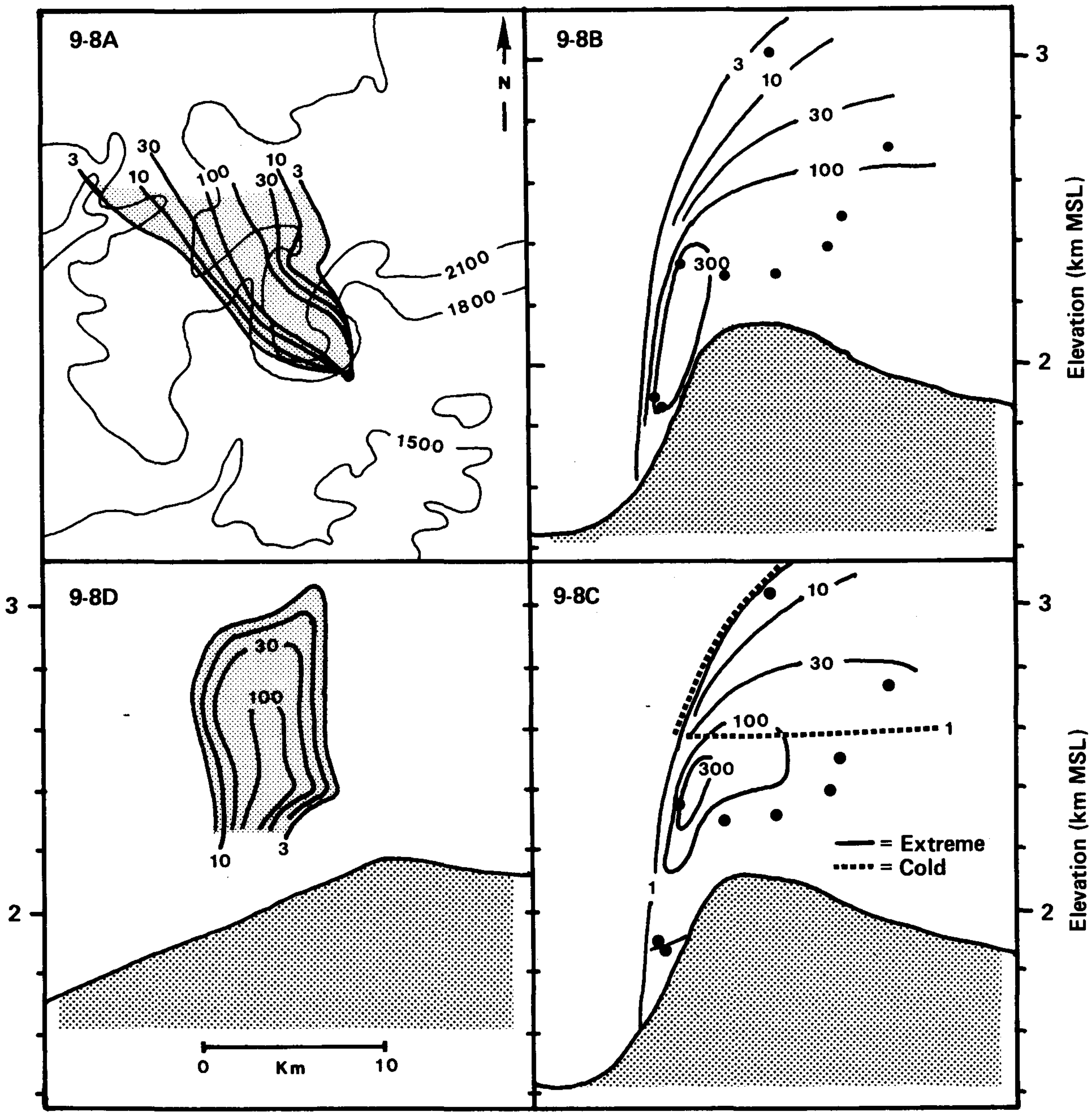


Figure 9-8A. - Horizontal structure of the SF_6 plume of March 2, 1987. Concentrations are in ppt. Ground elevation contours are in meters above sea level. The horizontal scale is the same as for figure 9-8D. Aircraft sampling was done at positions shown in figure 9-8B.

Figure 9-8B. - Vertical cross section of the SF_6 plume of March 2, 1987, along its centerline. Dots represent individual aircraft passes through the plume. Concentrations are in ppt. The horizontal scale is the same as for figure 9-8D.

Figure 9-8D. - Vertical cross section of the SF_6 plume of March 2, 1987, about 7 km downwind of the source. Concentrations are in ppt.

Figure 9-8C. - Estimated AgI ice nucleus concentrations per liter corresponding to figure 9-8B for "cold" and "extremely cold" storm conditions.

altitude. Though not simulating stable storm conditions, this experiment may be helpful for illustrating conditions in which orographic convective activity would lift the seeding materials rapidly to the cold tops of towering cumulus clouds.

9.5.7 Payson Airport, March 5, 1987. - The SF_6 plume was released during the latter half of the afternoon from the Payson airport in order to observe if the plume would be transported over the Mogollon Rim. A strong inversion existed above 3.1 km m.s.l. with near-neutral stability below. The skies were nearly overcast with thick cirrostratus patches that cast dark shadows on the ground. Figure 9-9A shows how the plume generally traveled north-northwesterly and passed over the escarpment. The last passes, close to the release site, were near sunset when diurnal changes in the wind regime probably caused the apparent meander to the north-northeast. The plume was probably straighter at earlier times. The aircraft actually was ahead of the plume far to the north, arriving there before the average windspeed could advect the plume that far. It is likewise probable that the first descending passes over the crest of the Mogollon Rim were made just as the plume was arriving there and before steady-state conditions had been established.

The vertical cross section along the plume is shown in figure 9-9B. Peak SF_6 concentrations reached in excess of 100 ppt over the crest. When translated into the expected active ice nuclei concentrations in figure 9-9C, concentrations reached over 20 L^{-1} for the extremely cold storms but only a trace at the top of the plume for the cold storms. The use of exotic AgI produced light (< 7 L^{-1}) concentrations only higher than 2.6 km m.s.l. Any snow generated from a similar and real AgI plume would probably have fallen in the drainage of the Little Colorado River to the north of the Mogollon Rim. Only one transverse cross section, over the Mogollon Rim, is presented in figure 9-9D; but it was sufficient for the calculation of the vertical as well as the horizontal dispersion coefficients.

9.5.8 Mingus Road, March 9, 1987. - The releases of SF_6 from Mingus Mountain were intended to show any advantage in a high-altitude release for getting ice nuclei to even higher (colder) altitudes at which the nuclei would have increased effectiveness. The experiment occurred in air that had an icy cloud band with radar echoes generally from 2 to 6 km a.g.l.

Unlike other plumes, the plume from this release kept rising and, apart from its origin, was not connected to the ground. Figure 9-10A shows that the plume path projected on a horizontal plane was highly bent as a result of wind shear encountered as the plume climbed to higher altitudes. The meanders were consistent with the wind directions measured by the aircraft, starting with west-southwesterly at the release site in the notch of the mountain. The discontinuity in the 100-ppt contour reflected the difficulty of tracking the rising plume in three dimensions.

A plane oriented 305 to 125 degrees was chosen for the x-z projection shown in figure 9-10B. Mingus Mountain was shown as double peaked even though an exceedingly thin cross section would not show both peaks at that orientation. The plume may have been rising at a steady rate, but the wind shears caused the plume to be moving more perpendicularly to the x-z plane at the start and end of the mapping. The tops and bottoms of the plume at various locations were not usually located; the flight crew had a difficult time staying near the core.

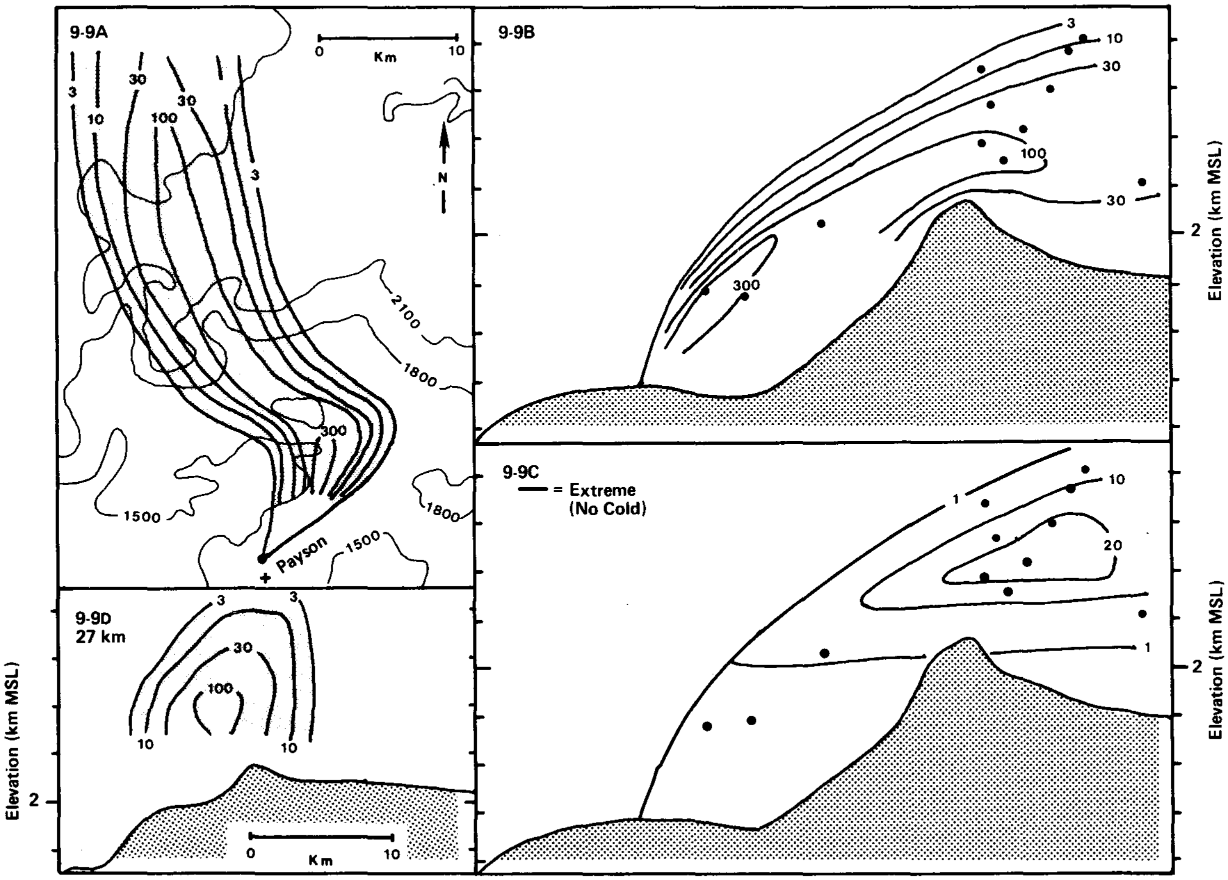


Figure 9-9A. - Horizontal structure of the SF_6 plume of March 5, 1987. Concentrations are in ppt. Ground elevation contours are in meters above sea level. Aircraft sampling was done at the positions shown in figure 9-9B.

Figure 9-9B. - Vertical cross section of the SF_6 plume of March 5, 1987, along its centerline. Dots represent individual aircraft passes through the plume. Concentrations are in ppt. The horizontal scale is the same as for figure 9-9D.

Figure 9-9D. - Vertical cross section of the SF_6 plume of March 5, 1987, about 27 km downwind of the source. Concentrations are in ppt.

Figure 9-9C. - Estimated AgI ice nucleus concentrations per liter corresponding to figure 9-9B for "extremely cold" storm conditions.

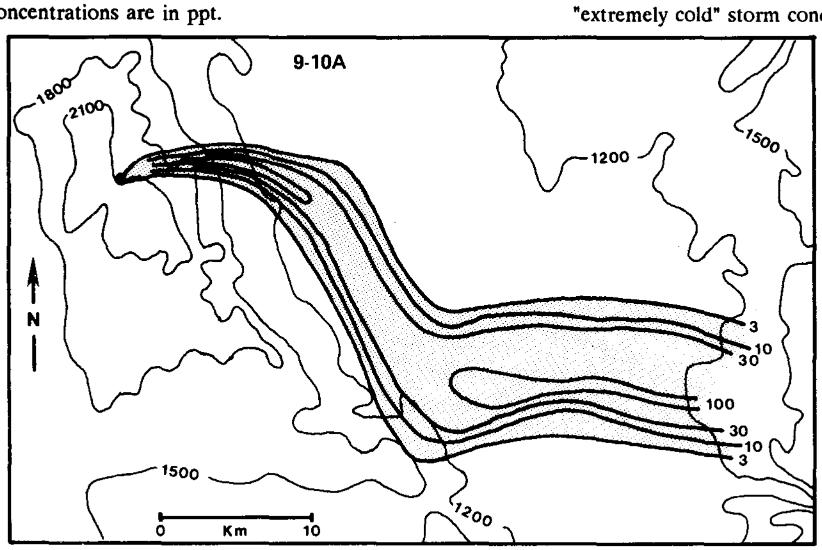


Figure 9-10A. - Horizontal structure of the SF_6 plume of March 9, 1987. Concentrations are in ppt. Ground elevation contours are in meters above sea level. Aircraft sampling is discussed in the text.

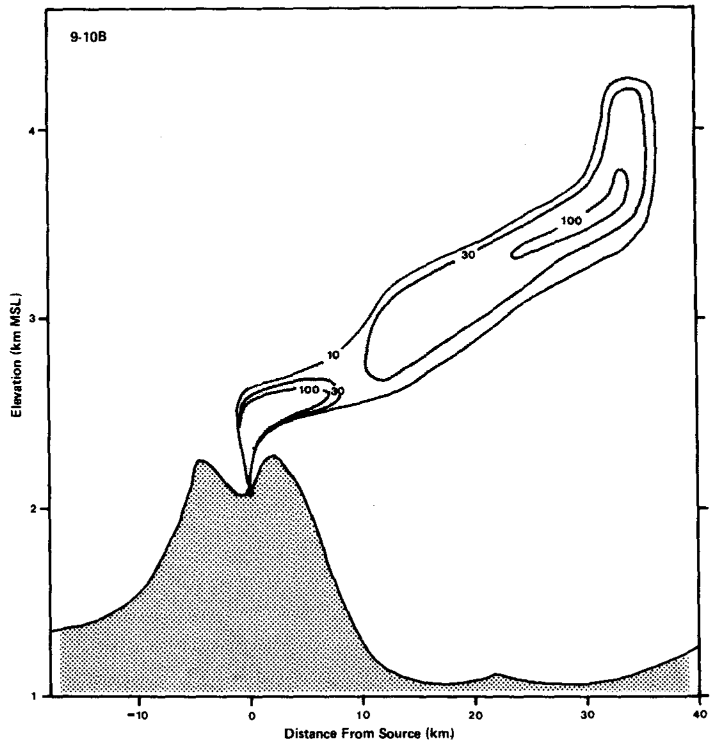


Figure 9-10B. - Vertical cross section of the SF_6 plume of March 9, 1987, along its centerline. Concentrations are in ppt.

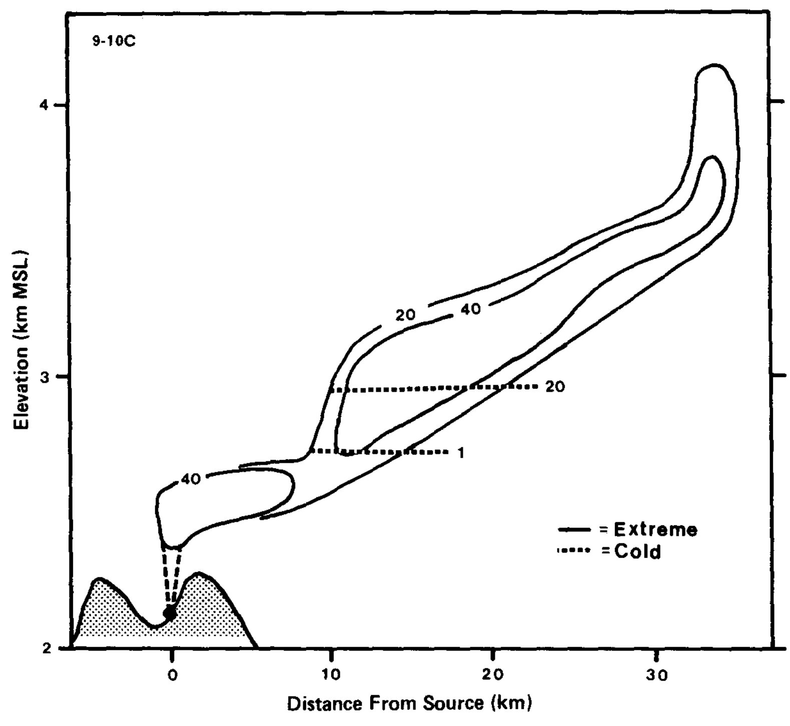


Figure 9-10C. - Estimated AgI ice nucleus concentrations per liter corresponding to figure 9-10B for "cold" and "extremely cold" storm conditions.

When the SF_6 concentrations were converted into AgI ice nucleus concentrations, a plume in excess of 40 L^{-1} was indicated (fig. 9-10C) for the extremely cold storms and for the upper two-thirds of the plume in the general cold storms. The nuclei became appreciably effective in the upper half of the plume under typical storm conditions above 3.5 km altitude. There was even 1 to 2 L^{-1} (20 L^{-1} with the exotic AgI) ice nuclei produced near the extreme top of the plume (4 km altitude) under the warmest conditions. No other SF_6 experiment yielded such satisfactory simulated ice nucleus concentrations for the normal and warm storm conditions. But in view of the unusual profile of this plume, more mountain release experiments are needed to confirm this as being a useful seeding strategy.

The plume was always high above ground, and the extremities were not well mapped; therefore, the y-z cross sections were not presented. The Gaussian plume model given in equation (9-1) is for a plume whose highest concentrations are at the ground. That was not the case in this experiment.

9.5.9 Mingus Road, March 16, 1987. - Airspace traffic conflicts precluded the sampling aircraft from doing a proper study of the plume, so the interceptions were only occasional. The experiment took place in actual storm conditions; the plume rose to about the 3.5 km level. It is strongly suspected that most of the plume was missed. No cross sections are presented here, and the plumes were not sufficient for determining dispersion coefficients. Even so, there were three plume interceptions in which a comparable AgI plume gave an average effective ice nucleus concentration of 15 to 20 L^{-1} in the extremely cold storms.

9.6 Summary of SF_6 Experiments

It is seen from these experiments that plumes of ground-released SF_6 can indeed rise over the ascending terrain to cross the crest with a plume height of over 700 m under normal storm conditions with neutral stability. Dispersion constants for the horizontal and vertical extents of the plume are comparable with values determined for plumes over flat and level terrain. Models, such as a Gaussian diffusion model in equation (9-1), can be used to describe a plume, provided that the altitude (z) used is the height above the generally varying terrain.

Effective ice nucleus concentrations in the plumes can be estimated from model aerosol concentrations by use of equations (9-4) and (9-5) for appropriate ice nucleus effectiveness curves and actual temperature profiles. Adjustments in equation (9-1) could be made for vertical wind shear.

Most of the actual SF_6 experiments, when the temperatures were adjusted to storm conditions, indicated that ground-released AgI from the Montana State University generator would be an effective seeding agent only for the extremely cold storms. The simulations with the exotic nuclei (not shown) indicated adequate concentrations during the general cold storms. A further improvement would likely be achieved by using fans on the generators to reduce coagulation of the AgI aerosol. It is again noted that these simulations were based on cloud simulation chamber data for seeding generator output of ice nuclei. Possibly, future measurements in actual clouds will reveal greater or lesser outputs from the generators so the results presented should be considered tentative. Moreover, further experiments should be conducted when embedded convection is present that may enhance vertical mixing. Tables 4-1 and 4-2 showed that storm periods with some convection were quite common. Such periods may be more seedable from the ground than stratiform cloud periods.

The Mingus Mountain experiments indicated that high-altitude release would give the seeding materials an advantageous lift to colder temperatures where they would be more effective. But such sites are not widespread, and access is often difficult. With exotic nucleus complexes and natural draft generators, AgI nuclei released from sites lower than the Mingus Mountain site would effectively seed only about the coldest third of the stratiform winter storms of Arizona. As noted, evaluation of the seeding potential of the convective storms needs more experimentation.

Other studies have indicated that the flux of SLW over Happy Jack was independent of 700-mb temperature during storm conditions; therefore, there is no bias in liquid water opportunities related to seeding only the colder storms.

Treatment of the warmer storms may have to rely on (a) generator fans for a slight improvement, (b) convection to lift the nuclei higher into the clouds than would be indicated by these experiments and the models, (c) release of AgI nuclei from aircraft or from upwind mountain peaks, or (d) dropping dry ice pellets (solid CO_2) into the clouds from aircraft. Items (b) and (c) could be simulated with more SF_6 experiments. Eventually, experiments with real AgI nuclei or dry ice pellets will be needed to verify these conclusions in real clouds.

Some additional investigations of the SF_6 experiments were made to examine continuity of released mass and relative conditions inside and outside the plume. The flux of SF_6 through the plane of a vertical cross section was estimated for the six experiments that had data appropriate for such a study (January 30; February 3 and 15; and March 2, 5, and 15). The resulting fluxes, in kg h^{-1}, were compared to the rate at which gas was released. What was found, though it was not a precise determination, was a mean of 21 percent ± 5 percent of what was released, with a range of 14 to 30 percent. Though some of the gas may have remained close to the ground where the aircraft could not sample, other reasons for the discrepancy have not been identified. In the conversion from SF_6 concentrations to effective ice nucleus concentrations, it was assumed that unexplained losses would be the same for AgI; that is, the ratios of concentrations of SF_6 actually found to the rate of release were assumed to be the same for AgI.

Conditions inside the plume were compared with those immediately outside the plume for several parameters. When averaged over all plumes, the interior conditions were generally 0.1 °C colder, had a relative downdraft of 0.1 m s^{-1}, and were slightly more turbulent. Such differences are smaller than the resolution of the instruments so little significance should be applied to them; the differences are, however, consistent with an understanding that the plumes are in surface air that has risen just past the limit of its buoyancy. Many passes were at the tops of the plumes.

These SF_6 experiments have been used as a substitute for actual cloud seeding to simulate the behavior of ground-released AgI aerosol. The results and further numerical simulations indicated that stratiform Arizona clouds were usually too warm for effective cloud seeding by generators like the Montana State University design when using a standard AgI-NH_4I aerosol. Improvements, such as exotic complexes and fans on the generators, may make the coldest third of the storms available for effective seeding by ground generators;

and convective mixing may further aid ground-based seeding. However, alternative seeding strategies, such as aircraft seeding, should be addressed by future experiments.

10. CONCLUSIONS AND RECOMMENDATIONS

Observational programs of natural clouds and precipitation processes were carried out in two different high-elevation regions of Arizona during mid-January to mid-March of 1987 and 1988, respectively. The main purpose of these programs was to investigate the degree to which Arizona winter clouds over the Mogollon Rim are suitable for precipitation enhancement by cloud seeding. The availability of CLW is of key importance to such an assessment, and the CLW was monitored by surface and airborne instrumentation. Several other factors pertinent to estimation of cloud seedability were observed. Examples include concentrations and types of natural ice crystals, cloud depth, atmospheric stability, wind velocity, and the general weather situations that produced apparently seedable clouds. An important secondary purpose of the 1987 field program was to conduct transport and diffusion experiments with a tracer gas to assess the potential of ground-based seeding over the Mogollon Rim.

Several conclusions became apparent during the analyses presented in this report. Most important, the CLW necessary for cloud seeding potential existed during at least portions of most of the storms studied. Estimates of the flux of CLW over the crest of the study areas indicated relatively large values. The estimates, extrapolated to 4-month winter periods, range from about 30 to 100 percent of the mean annual runoff from nearby high-elevation watersheds. It is not presently known what fraction of the CLW could be converted to snowfall by cloud seeding, but the presence of abundant CLW is encouraging.

Most of the CLW flux was concentrated in a few widespread storms that lasted from about 1 to 3 days. These storms already produced significant snowfall but were inefficient in precipitation production during portions of their lifetimes. Periods with abundant CLW flux typically had moderate to strong southwest or west winds and shallow clouds with warm tops. However, there were important exceptions to this generalized portrayal, as when strong winds and associated orographic uplift apparently produced more liquid water than the ice particles generated by deep clouds could convert to snowfall.

Periods that appeared suitable for seeding often existed during the beginnings and endings of storms, and sometimes during middle stages as well. The duration of CLW occurrences varied from only an hour or so to many hours. Transitions were often rapid between periods when seeding could likely increase the snowfall and periods when it could not.

It is beyond current forecasting ability to predict accurately when and where seedable clouds will exist. It would even be very difficult to conduct seeding operations in response to real-time observations because of the rapid transitions in cloud conditions. The most practical strategy may be to seed throughout entire storms, assuming that seeding does not significantly decrease snowfall when the clouds are naturally snowing efficiently. While there is evidence from other regions to suggest this is a valid assumption, the first recommendation is to test this strategy in Arizona winter clouds.

The transport and diffusion studies revealed that ground-released AgI should routinely mix through the lower 0.5 to 1.0 km above the Mogollon Rim crest when stratiform clouds are present. Clouds with embedded convection would likely have even more vertical mixing, but these clouds were not well represented during the transport and diffusion experiments. Evidence from other analyses suggested that most of the CLW was often concentrated in the lowest kilometer or so above ground. However, examination of the temperature structure during storms revealed that this zone was often too warm for much ice crystal formation with conventional types of AgI used with ground generators. It is recommended that some seeding experiments be conducted with high output ground-based AgI generators using recently developed solutions that nucleate significant ice in cloud chambers at temperatures up to around -6 °C. These solutions need to be tested in actual Arizona clouds. Further, transport and diffusion studies should be expanded to cloud layers with embedded convection, which should enhance vertical mixing. Such convection exists during a large portion of the storm periods. Seeding releases from higher sites than those normally used during 1987 should also be attempted where the topography permits. Upwind ridges nearly as high as the target area would provide very desirable ground-release sites. However, even with the suggested approaches to increase the effectiveness of ground seeding, it is anticipated that a large fraction of Arizona winter storms will require aircraft seeding.

The presence of a reasonable frequency of apparently seedable winter clouds has been established for the high elevation portions of the Mogollon Rim. It is recommended that a several-year program be implemented to document the amount of additional precipitation and streamflow that can be obtained by cloud seeding, how reliable this new source of water will be, what environmental and social impacts might be associated with cloud seeding in Arizona, and what the costs of a future operational program would be. The first steps in such a program should involve the development of detailed plans for seeding experiments, assessment of environmental impacts, and public involvement.

It is recommended that the next few field programs be devoted to a series of experiments to monitor the physical "chain of events" following cloud seeding. The measurement program should be comprehensive enough that the degree of success of each experiment could be evaluated from physical evidence, and the reasons for success or failure to produce additional snowfall on the target area could be determined. Recent improvements in knowledge and instrumentation make such experiments practical as demonstrated in California, Colorado, and Montana during the past few years. These experiments should include both airborne and ground-based seeding with a number of seeding agents and should be applied over a reasonable range of cloud conditions. Analyses of these experiments would reveal whether further efforts are justified and, if so, would provide guidance in the design of a later randomized seeding program aimed at demonstrating seasonal snowfall increases over a target area. It is particularly recommended that adequate time and resources be allocated for analyses of the field measurements, as failure to do so has seriously hampered many past programs in weather modification. The recommended methodical, step-by-step approach should have a high probability of providing an important future source of water for Arizona.

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APPENDIX

DISCUSSION OF THE 1987 AND 1988 STORMS BY EPISODE

DISCUSSION OF THE 1987 AND 1988 STORMS BY EPISODE

The classification system of section 4.4 was used to identify the differing periods within each storm episode. As described in section 4.3, the initial S means synoptic, initial M means mesoscale, trailing S means stratiform, and trailing C means cumuliform. The hourly designations were presented in tables 4-1 and 4-2.

1. January 15-17, 1987: Periods SC, SS, SC, SS

As the upper air impulse for the storm development approached, a patch of stratocumulus clouds formed over the Mogollon Rim with some cloud streets having a southwesterly-northeasterly orientation. These clouds provided the early CLW (cloud liquid water) events but no precipitation at Happy Jack. By about 1300, the cloud character in the satellite and time-lapse photographs changed from generally cumuliform to generally stratiform. At about 1500, a frontal band arrived with snow; but the CLW generally remained through the night. The frontal band rose steadily from low clouds over southern California to very high cirrus over Colorado. Though the pattern of the CLW amounts resembled cumuliform activity, a better explanation in this case might have been that bands of ice particles from the cirrus level (contoured in the infrared satellite photographs from about 1700 on January 15 to 0100 on January 16) fell into the lower level CLW and consumed it. Without this natural seeding from above, the CLW graph would have been a semi-smooth hump as the strong southwesterly winds created a low-level stratiform orographic cloud over the Mogollon Rim. After the passage of the frontal band at about 0100, only low-level stratus and stratocumulus clouds remained, which had a diminishing mixture of CLW and snow. By 1200, the cumuliform nature began to dominate again as shown in the photographs; and the precipitation became showery. Towards sunset, the solar energy driving the convection was cut off, the skies generally cleared, and neither CLW nor snow was left at most sites during the first part of the night.

Later in the night (there was a brief CLW episode from 2400 to 0100), an apparent windshift occurred. All day on January 17, the clouds appeared to be suppressed stratus and stratocumulus in upslope flow from the northeast. This lingering activity produced no CLW at Happy Jack and only light amounts of snow.

2. January 19-20, 1987: Period SS

This episode was entirely an upper air system devoid of surface fronts as a trough slowly passed over the region. The trough axis appeared to contain a broad band of thin cirriform clouds. Stratus and stratocumulus clouds were adjacent to the high clouds in other parts of the state. During the daylight hours of January 19, some lower orographic clouds could be seen through the cirrus, mainly near the 1200 appearance of a small amount of CLW above Happy Jack; but all snowfall thereafter was without the presence of liquid. During the night hours, that cirriform patch was contoured as shown in the infrared photographs, giving a signature that usually indicates the lack of lower level CLW below. Eventually, the cirriform shield moved to the southeast. The morning satellite photographs indicated a large stratus patch on the north side of the Mogollon Rim, filling most of the Painted Desert. The edge of this stratus apparently drifted over Happy Jack for a few hours just before 1200 on January 20. The departure of the stratus marked the end of this episode.

3. January 23, 1987: Periods SS, SS

A major Pacific frontal system disintegrated upon reaching the coast, but the system's clouds continued inland. The system brought in tropical air all the way from the intertropical convergence zone, according to the continuous stream of clouds back to that region. But by the time the system reached Arizona, only the high-level moisture and jetstream winds remained. During the morning, the rear end of the cirriform band passed over the project area accompanied by a patch of thick altocumulus. At least virga was falling from those clouds possibly reaching the ground but not creating measurable precipitation. With the cirrus passage, CLW began to appear starting at 0900 and lasting for about 2 hours. The satellite photographs showed stratus to the northeast of the Mogollon Rim, but the edge of that patch did not appear to have moved towards Happy Jack. Instead, the time-lapse photographs recorded patches of lenticular mid-level clouds over the Mogollon Rim.

Near 2400, the upper level trough associated with this episode passed over the area. As shown on the nighttime infrared satellite photographs, some small patches of low- or mid-level clouds were barely visible. These clouds must have been responsible for the brief pulse of CLW from 2300 to 2400.

The approach of this period was easy to forecast, but the low-level air was too dry for much precipitation or cloud liquid activity over the Mogollon Rim. The appearance of CLW after the cirrus passage was normal, and there was low-level moisture in the stratus just downwind of the Mogollon Rim. This episode almost became of interest concerning cloud seeding potential.

4. January 27, 1987: Period SS

On January 26, there was a patch of tropical moisture southwest of California drifting slowly northwards. This patch had already severed its roots from its source region and arrived over Happy Jack about 0500 on January 27, bringing altocumulus clouds with some unusual conically shaped virga and small amounts of CLW between 0600 and 0900. That brief episode was also accompanied by a large increase in vapor values. Thereafter, the tropical moisture only brought increasing cirriform and altostratus clouds, also with virga.

5. January 28, 1987: Period SS

Meanwhile out in the Pacific, a major cold front collided with the tropical moisture producing a large patch of clouds. On January 28, a significant band of CLW was detected. The tropical moisture had been squeezed into what looked like a frontal band preceding the actual Pacific cold front. No CLW was detected under this cirriform canopy until after 0800. Then the cloud base changed from an altostratus with virga to a slightly undulating altostratus generally free of ice. Temperatures in the cloud base were generally warm, possibly warmer than 0 °C. There was a small break in the clouds at about 1040 when the rear of the cirriform canopy reached the project area, but the low-level clouds quickly returned to altostratus and broke up to altocumulus as the episode ended about 1300. While it is common to have the CLW appear after the passage of a cirriform canopy, the period from about 0820 to 1040 was unusual. The jetstream winds apparently created a vigorous liquid cloud that may have been separated from the cirrostratus by a dry layer that prevented the ice crystals from reaching the lower CLW.

6. January 28-29, 1987: Period SS

This brief episode occurred from before 2400 to 0600 on January 29. The episode produced some patches of CLW, apparently out of an altostratus deck that was not overrun by high cirrus due to an approaching short wave in the upper flow. No surface precipitation was recorded.

7. January 30-31, 1987: Period SS

A Pacific cold front approached the California coast during the days preceding this episode. The front developed a north-south orientation. The front reached the coast at about the same time that the infrared satellite photographs, which were tuned to the moisture part of the spectrum, revealed a strong narrow swath of cold dry air rapidly flowing south along the rear of the frontal clouds. These conditions led to the formation of a new vorticity center off southern California and then created a new low center in Arizona. As the low passed over the Happy Jack area, the storm system was examined by the aircraft on January 30 and 31. The storm is described in more detail among the case studies of section 7.

After the passage of the typical cirriform shield ahead of the storm, the frontal band passed into the area. In this storm, the tall clouds were behind the front but were not devoid of significant CLW. Apparently, the strong winds created a low-level orographic component of CLW; the falling snow from higher levels was not of sufficient intensity to consume all the CLW.

Eventually, there was a gap in the clouds seen by the radar and satellite photographs. Near sunrise, another band, arcing as an innerspiral arm around the new low that had formed during the night, arrived over the project area. Comparison of the sequence of satellite photographs showed obvious rotation of the cloud band around the center of the low. The spiral band brought the heaviest precipitation period of the storm to Happy Jack but still did not exhaust the CLW.

After the passage of the spiral band, a clearing passed over the Happy Jack area with presumably low clouds only. As the storm center passed to the northeast, the circulation around the back side brought a low-level stratus cloud with upslope conditions. The moist surface air under northerly flow released an abundance of CLW as the air was forced uphill over the Mogollon Rim. This cloud was not seeded naturally by any ice particles from higher clouds. Some natural graupel and needles were present but only in low concentrations, which did not efficiently consume the liquid. The SLW (supercooled liquid water) content of the cloud was sufficient to heavily rime the aircraft to the point where it had to repeatedly climb above the clouds to shed the accumulated ice of each pass. The stratus appeared to have had a stronger convective nature in the late afternoon of January 31 just as the episode was ceasing.

8. February 4, 1987: Periods SS, SC

This episode was mostly the passage of an upper air trough; the surface front associated with the trough decayed over Arizona as the activity began. There was initially a persistent band of high clouds associated both with the front and the jetstream. As the episode developed, the cirriform clouds moved east and the organization diminished. Meanwhile, a low-level patch of cloudiness lingered over Arizona eventually getting behind the upper trough axis. The onset of CLW at Happy Jack appeared to be behind the remnants of the front. The time-lapse photographs showed the cloudiness to be initially stratiform in basic character though composed of both altocumulus and stratocumulus. At 1200, the character changed as the altocumulus clouds, which were held down by an apparent inversion that suppressed the stratocumulus clouds as well, evaporated and allowed solar heating to create vigorous towering cumulus clouds and accompanying graupel showers. After sunset, this activity subsided.

9. February 5, 1987: Period MS

The northeasterly winds of the previous system kept low-level moisture in the Painted Desert basin. During the night, the winds became strong and created an orographic patch of stratus along the northeast side of the Mogollon Rim. Apparently, some of the cloud edges extended as far as Happy Jack and created trace amounts of CLW for the first 5 hours of the day.

10. February 9-12, 1987: Periods SS, SS, MC

On February 5, there was a small cloudy patch on the intertropical convergence zone southeast of Hawaii. By sunset that day, the patch started to enlarge. By 2400, it was rapidly extending to the northeast apparently in response to a developing wave on an old Pacific cold front to the north. The new circulation center on that front was about midway between Hawaii and California at that time. By 1200 on February 6, the tropical moisture band extended from its original position to about three-fourths of the way to California and was actually getting ahead of the storm system that may have drawn it up from the equatorial regions. The leading edge reached the coast at 1500 on February 6. By 2400, the moisture was in a band extending only slightly east of true north all the way from the equatorial region to central Nevada. Over February 7 and 8, the moisture band wrapped around the low to the west, generally broadened, and became less organized. During these days, central Arizona had only cirriform clouds.

Meanwhile, there was another Pacific cold front coming in behind the low. This frontal system may have ingested some of the tropical moisture being wrapped around the low. The southern part of this frontal system eventually accelerated eastward as the original low moved to the coast and dissipated. A cirrostratus band detached itself from the front and passed over Happy Jack in the early daylight hours of February 9, apparently producing a trace of CLW. The lower remnant of this latter front brought the first significant CLW of the episode to Happy Jack at 2100 on February 9. The nighttime cloudiness of this frontal remnant was judged mainly stratiform in the satellite photographs; then the upper level wave that generated this cloudiness stagnated and the organization diminished. What was left was a generally moist and unstable atmosphere throughout a very wide area. At about 0800 on February 10, this atmosphere with solar heating started generating cumuliform showers particularly near midday for the next several days. Tropical moisture was probably involved but had been diluted by other sources of air over several days.

On February 12, another frontal remnant with its accompanying upper air short wave passed mainly north of the state. This remnant had a north-south orientation and seemed to weakly tap into tropical moisture again. A vorticity center formed in central Arizona and contributed to the largest cumulonimbus cells of the episode; but those showers were partly orographically triggered. The skies cleared during the afternoon of

February 12 as that several-day episode of moist and unstable skies were swept away to make room for the next system.

11. February 12-13, 1987: Period SS

The arrival of this episode logically began after 2000 on February 12 as a north-south thin instability line passed over the project area and then dissipated by sunrise. This episode brought a good pulse of CLW plus some measurable rain. In opposition to the usual diurnal cooling, the air temperature rose several degrees with the passage of this line. The winds shifted from westerly to southerly. The satellite photographs traced the cloud feature back in time and showed that the cloud feature was once the leading edge of a frontal patch of clouds and moisture, which appeared to be a warm front north of Hawaii (February 11). The existence of this warm front explains the winds, moisture, and temperature of the cloud feature. The daylight satellite photographs just prior to the arrival of this band showed the cloud feature to be semitransparent cirriform clouds with no lower clouds. Apparently, a lower orographic cloud was generated near Happy Jack to produce the observed CLW and rain. The episode ended by about 0400 on February 13.

12. February 13-14, 1987: Periods SS, SC

The episode was a continuation in the same air mass brought in by the warm front remnant on the previous evening. The warm moist air had originally come off of the intertropical convergence zone southwest of Hawaii and then passed north of those islands before coming to California. This part represented the passage of the trailing cold front remnant. By the time the front arrived at Happy Jack, it was difficult to identify the time of passage. The first precursor clouds were a deck of altocumulus at about 1100, which gave a trace of CLW. After 1430, CLW returned mostly in the form of cumulus clouds. A tall, apparent cumulonimbus system, according to the radar and satellite photographs, passed over Happy Jack at about 2130 bringing a small amount of rain. A shallower cell at 2400 brought a major pulse of CLW but little measurable precipitation. The anvil cirrus above this cell was not connected to the lower cloud and marked the last of the high clouds that were contoured on the nighttime infrared satellite photographs. The rear of these high clouds was later recognized by weather map analysts as the new cold front position. The period of abundant CLW was from 0230 to 0730 on February 14. The satellite photographs showed only a field of very low clouds, confirmed by the radar, with some lumpy texture suggesting a cumuliform nature. There were no high clouds above this cloud deck. The episode was ended at about 0730 with the passage of the remnants of the original cold front, which brought another large pulse of CLW, slightly higher radar tops, a graupel shower, and some windiness.

13. February 15-16, 1987: Periods SS, SS, SC

The day began with the sunrise passage of the upper air part of a cold front remnant, bringing cirrus and altocumulus with CLW from 0730 to 0900. The surface part of the cold front was delayed until evening. The air mass, similar to the last one, came off the intertropical convergence zone south of Hawaii, passed over that state, and then traveled on to California. There were strong winds moving the air along at the upper levels.

A large patch of altostratus arrived with the precursors of the next apparent frontal band. The rear of the band passed from about 1930 to 2030 with a pair of tall clouds but only a trace of precipitation and CLW. A deck of low clouds prevailed over the area from about 2100 to 0530 the next day according to the radar. There were several patches of CLW observed by the radiometer. The end of the cloud deck was marked by another trace of snow; the surface winds then shifted from west-southwesterly to northerly.

The timing of the cold front was particularly difficult to determine. The remnants of the old upper front passed to the north about 0800 on February 15 and looked like a frontal passage at about 2000 according to the arc of cloud bands seen in the satellite photographs. A surface analysis suggested a surface frontal passage after 0200 on February 16; but the passage may not have happened at Happy Jack until about 0530 according to the cessation of the cloud deck and the shift to northerly winds.

About 1000 on February 16, the clouds became towering cumulus showers mostly of orographic origin but strongly aided by an upper air vorticity center and solar heating, according to the satellite photographs. The CLW of the convective clouds was detected at Happy Jack with only a trace of snow. The Payson time-lapse camera showed that the precipitation intensified as the showers moved south.

14. February 17-18, 1987: Periods MS, MS, SS, SC

The skies cleared after a trace of CLW from a thin patch of orographic altocumulus at sunrise. Later, thicker suppressed stratocumulus formed over the Mogollon Rim in westerly flow. The trough that was aloft did not have its own cloudiness. The satellite photographs showed the cloudiness to be well confined to the Mogollon Rim until 2000. Even though slightly convective, the general band of clouds was stratiform. Therefore, the first part of this episode can be given an MS classification even though synoptic and convective influences were present.

After 2000, another upper air short wave approached the area. The low clouds then began to appear in regions adjacent to and over the high ground. By morning, the time-lapse photographs again showed stratocumulus clouds; but the clouds were apparently being seeded by altostratus bands moving over them. The showers coming through the cloud bases seemed to have a different speed from the stratocumulus clouds. The upper level bands were weakly visible in the satellite photographs.

About 1200 on February 18, the region was under an upper level low. The lack of high cloudiness let solar heating create a more vigorous convection and accompanying showers. Sunset clearing then ended the episode.

15. February 19-21, 1987: Periods SC, SS, SC, MS

This is an unusual episode that can be divided into several parts with different characteristics. A low developed from the previous system and was centered in New Mexico but stationary. During the present episode, that low backed up over Arizona, degraded to a trough, and then resumed a more normal eastward movement farther to the south. During the daytime of February 19, the synoptically controlled system developed a westward extension over the Mogollon Rim. From 1000 to 1700, the clouds slowly grew from towering cumulus to cumulonimbus. The latter were thoroughly icy in appearance. The spikes of CLW measured by the radiometer kept increasing in intensity until about 1500. The period can be classified as SC.

This convective activity appeared to have filled the sky with debris, which then slowly settled out. The satellite photographs showed the high cloud band persisting over the high ground all night. The cloud band dumped aggregates at Happy Jack from about 2100 until about 0115 on February 20. There was a pulse of CLW in between cells at 2400. This period can be classified as SS because the activity was relatively stagnant.

The surface winds then became stronger from the east as the low began to retrograde. There was a period of very tiny particles of light intensity at Happy Jack for a few hours--a lull in the storm. Liquid water returned from 0300 to 0800. The high ice cloud band stayed present until 1200 but was disconnected from the lower layers of cloud while the CLW was present. This changed after 0700 as the easterly winds brought upslope snow in great quantities to Happy Jack. Aggregates were present until 1000, and then single particles existed. This upslope period until 1200 on February 20 can also be classified as SS though the period was from a differing mechanism than the previous period.

At 1200, the high ice cloud went away according to the radar and satellite photographs; and a 6-hour period of towering cumulus activity was present yielding little CLW at Happy Jack and little snow. This is another SC period as the convective activity was due to the trough and was not confined to the high topography. At about 1800, the surface winds became strong from the northeast. CLW resumed and lasted until 1000 on February 21, peaking at about 2200. The radar detected a deck of very low clouds from 2030 to 0300. This band was weakly visible in the nighttime satellite infrared photographs. The synoptic system was then to the south with a band of high cirrus marking its northern reaches. The clouds at Happy Jack, however, were not an obvious part of the synoptic system. These clouds were confined to the northeast side and top of the Mogollon Rim and appeared to be an orographic stratus created by the strong northeast winds. The band persisted in this position for 17 hours and is therefore given the MS classification.

16. February 23-26, 1987: Period SS

The local newspapers labeled the snowfall from this episode as the greatest snowfall in 20 years. The system began with an outbreak of cold air dragging a low down the Pacific Coast from Alaska. The low became stationary in Nevada, and short waves rotated around it. The cold front became nearly stationary over Arizona for the intense part of the storm. Later, a new low developed along the front to the south of the project area and brought another storm period. Thereafter, the back side of the storm system continued to bring cloud activity to the area until late on February 26. Though the several cloud systems during this episode had differing characteristics, all can be classed as SS.

There were three general periods with CLW water; the first two were during strong southerly to southwesterly winds indicating a strong orographic component to the storm even though the synoptic forces dominated the episode. The first CLW episode lasted about 30 hours and coincided with a period of strong southerly winds at Happy Jack that lasted from about 0900 on February 23 to 1700 on February 24. Yet that period of CLW had widely differing characteristics. The second liquid episode, during the early morning of

February 25, was only about 6 hours long. The third episode lasted 18 hours with only a light change in character with time; the southwesterly winds near the surface were lighter than in the other liquid periods.

The first part of the episode on February 23 was of moderately tall convective activity. The time-lapse camera only saw stratocumulus bases and showers passing. The field was very dense so the stratiform classification was given. This part lasted from about 0930 to 1730 with no snow and only moderate CLW; then the character changed. The convection became more vigorous, yet the cloud tops were still held down. From 1730 to 0500 on February 24, there existed the unusual mix of moderate to heavy precipitation and moderate to very large amounts of CLW. This was all in prefrontal air coming rapidly from the Pacific Ocean near Baja California. The rapid orographic lifting of the moisture apparently produced a release of condensate (CLW) that was too great for the natural precipitation mechanisms to fully utilize. This period was likely an especially good candidate for cloud seeding.

At 0500 on February 24, the high tops of the frontal bands had reached the area according to the radar and satellite photographs. The amount of CLW was suppressed by the great amount of snow from the higher clouds falling through the CLW. The snowfall was so intense that it was amazing any CLW remained at all. It is suspected that the liquid from 0500 to 1700 was in the lowest levels of the cloud, being recently condensed in the rise of the air over the Mogollon Rim.

The times of frontal passages became hard to analyze once the fronts became nearly stationary. The original cold front may have passed about 1300 on February 24, but analysts created a new trailing cold front that passed by Happy Jack just after 2000. There was a slight change in wind direction from southwesterly to southerly after 1700 and a gradual diminishing of the winds over the next 3 hours. At that time, the precipitation rate became comparably low; and there was more cellular structure visible in the radar echoes. CLW was essentially absent from 1700 to 0130 on February 25, coinciding with wind speeds of only 1 or 2 m s^{-1} at Happy Jack.

The high winds and CLW then resumed for about 6 hours with the greatest liquid amounts corresponding to the highest winds. According to the radar, it appeared that an upper trough passed just after 0200 on February 25 with a very sharp clearing of the upper clouds. The satellite photographs showed a large hole in the upper clouds advecting over the area; the hole's movement was traceable back to Baja California as an apparent subsidence clearing in the synoptic flow. The lack of high altitude ice crystals falling into the lower orographic stratus deck allowed that low cloud to be inefficient in producing precipitation so the CLW increased markedly. Thus, a period of about 6 hours was likely seedable. The behavior was much like the appearance of CLW after the rear edge of a high cirriform deck passes over the Happy Jack area.

After 0600 on February 25, the winds dropped in speed again; by 0800, the abundant CLW was gone. A new wave developed along the semistationary front that had passed through the area and brought renewed cloudiness to the project region with light precipitation, only trace liquid, and high clouds. The radar showed the tops steadily increasing in height to 2000. The first half of this new storm period had the greatest precipitation amounts.

By 2100 on February 25, according to the radar, the cloud bases had risen. After 2300, new low-level CLW appeared that was not connected to the higher clouds. A low orographic stratus seems to have been present from 2300 to 1800 on February 26. The cloud deck developed some cumuliform features after 1400 from solar heating. The amount of CLW seemed somewhat correlated with the speed of the near-surface winds. A low, poststorm deck of orographic stratiform clouds, which did not precipitate significantly, appeared to be similar to decks associated with several other storms. This time, the temperatures (about -5 °C at the surface and about -15 °C near cloud top) were ideal for AgI (silver iodide) seeding (some similar decks were too warm). However, a real concern with seeding this particular storm was that it already produced record snowfalls.

17. March 2, 1987: Period SS

The only remnant of a former Pacific cold front and upper air trough, this period brought a small patch of altostratus to the Mogollon Rim area. Liquid, probably created by orographic lift, lasted in small amounts from about 0730 to 0945. The time-lapse camera did not show any low cloudiness.

18. March 6-7, 1987: Period SC

The moisture and impulse for this episode was traceable back to a north-south Pacific cold front with moisture roots in the intertropical convergence zone. The front took many days to move in from the coast and sent only bands of cirriform clouds over the project area from March 4 onwards. Eventually, the tropical moisture connection moved eastward into alignment with the central axis of Mexico and started to be cut off from its source. A northwest-southeast upper trough with a weakening low was the main feature that remained when the episode started. The surface front was only a remnant and was downgraded to a trough by some analysts. The cloud activity of this episode was driven by the residual moisture being lifted by the tall convective activity associated with the center of the upper air low.

The liquid activity began about 2300 on March 6 as the frontal cirriform clouds passed to the east. The first of three precipitating mesoscale systems within the synoptic low came between 0200 and 0500 on March 7. Surface winds shifted from westerly to southerly to easterly with this passage. Surface temperatures were warmer than 0 °C at the start of the band. Therefore, some of the precipitation may have been in the form of rain that artificially increased the CLW signal detected by the radiometer. Moderate amounts of liquid were measured, but little precipitation was recorded. Cloud tops were only moderate.

A tall cumulonimbus system then passed over Happy Jack about 0900 to 1100 with some good spikes of CLW and a greater amount of precipitation. Winds shifted back from easterly to southwesterly with the system's passage. The Happy Jack surface air was warmer than the melting temperature, but the ground 2D-C images, which were mostly graupel-like, did not show significant melting. The observers noted graupel, wet snow, and some rain.

The last cumulonimbus system was overhead from 1500 to 1800. With even more solar heating contributing, the system produced the greatest amounts of CLW and precipitation. Surface winds reverted to southeasterly after 1600 and then returned to southwesterly. The end of the episode marked the passage of the upper low. The precipitation type was again wet graupel and rain with most 2D-C images not showing much melting. There was a trace of CLW just before 2400, apparently from a remnant of the convective activity.

19. March 8-9, 1987: Periods SS, SC, SS

This episode gave the weather forecasters problems. The moisture came from some low stratocumulus fields that had been lingering for several days in the Pacific to the southwest of California. Though these cloud fields were somewhat aligned with the cold fronts to the west, there was no front assigned to them, not even an upper air trough. Eventually, the cloud patch was squeezed against the California coast by the cold front to the west. An upper air trough and increasing high cloudiness developed. The trough then moved inland over Arizona to begin the episode; the trough never had any surface fronts, and even the upper trough was more visible in the satellite photographs than in the upper air maps.

The CLW amounts from this episode were large. Some of the signal could have been from rain in the afternoon because of the warm temperatures then. Hand notes for the afternoon mentioned rain in the showers. The first shower near 0800 was only small graupel with temperatures right at 0 °C. Thereafter, light showers occurred possibly with rain. The time-lapse photographs showed stratus and stratocumulus until just before 1400 when the cumulus became more isolated. The stratiform class has been selected for this period.

During the cumuliform part of the episode, the radar showed that most of the clouds were still of restricted height; yet every hour up to 2000 had measurable precipitation. Very tall cumulonimbus systems passed over Happy Jack from about 1630 to 1830 and then from 2200 to 2300. The latter system produced the most precipitation; the passage marked a transition from convective back to stratiform for the remainder of the episode. The period 2000 to 2200 might also be called stratiform. The highest surface windspeeds were observed then and the highest sustained CLW amounts (about 0.25 mm) with almost no precipitation recorded.

During the early morning hours of March 9, the CLW amounts were light. The radar showed only traces of low clouds. Windspeeds were moderate. The rear of the cumulonimbus cloud at 2300 probably marked the trough passage.

20. March 10, 1987: Period MC

Another frontal remnant passed over the Happy Jack region with a cirriform shield lasting from about 1700 on March 9 to 0400 on March 10. There was no CLW observed and no precipitation; but the system apparently carried some low-level moisture behind it. A short wave in the upper air plus solar heating produced convection that was confined to the high ground of the Mogollon Rim. Liquid water was observed after 1100 with some tall spikes in the data from about 1230 to 1430. The last CLW was seen just after 1600 as the solar heating was decreasing. The radar saw only moderately high convective activity. No precipitation was observed at Happy Jack.

21. March 15-17, 1987: Periods SS, SC, SS, MC

The last major storm of the 1987 field season was a Pacific polar cold front that developed a wave and then a major low after reaching the California coast. The front wrapped around the south side of the developing low and crossed Arizona. After the passage of the trailing low across the state, the moisture that had traveled around the north side of the low to the west side came across the state. Finally as the storm passed away, the residual moisture developed into the orographic convection confined to the high ground.

Prior to the storm, the clouds were a very high cirriform with top temperatures about -50 °C. Only a trace of CLW was found with these clouds at about 0140 on March 15. The high clouds ended at about 0800 in the Happy Jack region in agreement with the radar echoes. Large amounts of CLW appeared after 0600 even with continuous radar echoes from near the surface to over 8 km m.s.l. CLW was apparently being produced by high winds crossing the Mogollon Rim. The satellite photographs showed a subsidence clearing to the northeast.

The next major band started over Happy Jack at about 0815 and lasted to the frontal passage at about 1300. When the visible pictures became available well after sunrise, a triangular shape with a narrow south-southwesterly origin was visible, much like severe thunderstorms in the Plains States but not having such prominent contouring in the infrared satellite photographs. This band, the rear of which coincided with the cold front, also terminated in the subsidence zone beyond the Mogollon Rim. The satellite photographs suggested that this band was dynamically well organized, ingesting tropical air at its origin at the north end of the Gulf of California, slowly raising the moist air to the center of Arizona, and then presumably dropping precipitation.

The pattern of CLW between the snowing bands continued after the frontal passage. The snowfall rate continued high from some postfrontal clouds to 1500 and then abruptly dropped to near zero by 1510. After the frontal bands had all passed, the character of the clouds changed. The satellite photographs showed the clouds to be broken to scattered convective rather than mostly stratiform; this reflected the typical cold air postfrontal instabilities with such storm systems. The 700-mb air temperatures soon fell to about -10 °C. The clouds were closely associated with the center of the upper air low. This convective period lasted from about 1500 on March 15 to about 0900 on March 16. Liquid water values were light to moderate, precipitation also light to moderate, and cloud tops not excessively high. The cloud bases were apparently low; supercooled fog was recorded at Happy Jack from 2400 to 0700.

After 0900, the radar indicated that the clouds became a shallow stratiform deck (the Payson time-lapse camera showed fog all day) with traces of cirriform clouds high overhead. Eventually, a thick high cloud connected with the lower layers to produce a heavier snowfall and reduced CLW. These clouds were basically a stratiform band that had wrapped around the back side of the low. The tallest band at about 1800 marked a trough passage during which the upper winds shifted from northwesterly to northerly. The graph of the CLW shifted from a spiky nature, suggestive of stratocumulus, to a semismooth plot with coarser variations, suggestive of an orographic stratus cloud. In fact, Happy Jack was again in supercooled fog from 1900 on March 16 to 0600 on March 17 as indicated by the icing rate sensor on a nearby tower. Radar cloud tops were moderate to 2400 and then shallow or not detectable. The stratiform CLW ended about 0630.

On March 17, the final day of the 1987 field season, the satellite photographs showed small convective cloudiness that was confined to the high ground of the Mogollon Rim. The clouds were generally shallow and produced light amounts of liquid water. Measurable precipitation missed most of the gauges.

22. January 15-17, 1988: Periods SS, SC

The first storm episode of the 1988 field season started with zonal flow on January 15 that brought a large cirrus shield ahead of a Pacific cold front. At 1340, the cirrus became thick cirrostratus at Alpine, Arizona; and at 1540, an altostratus deck was added with increasing virga towards sunset as a series of cloud bands advected across the area. By about 0200 on January 16, the highest cirrus had passed east of the Arizona-New Mexico state line.

Snow at Alpine began with the windy arrival of the frontal passage at about 0530 on January 16. Snow from the frontal band ended at Alpine at 0935 as a regime of stratocumulus showers began. The northeast-southwest orientation of the front and the westerly winds aloft made events occur at the town of Alpine earlier than at the Hannagan Meadow field site (see fig. 2-1).

Snow at Hannagan Meadow also began before 0600 and accumulated about 25.4 mm in depth by 0706 and another 19 mm by an hour later. This intense snowfall was composed of a high concentration of tiny particles with some small graupel.

Just prior to 0800, there was a change in conditions as an upper level band, shaped like a weak cold front, slowly moved over the area. Water vapor sharply increased, and the first CLW appeared and lasted as a broad band for about 1.5 hours. The precipitation rate decreased, and the presence of a high concentration of needles was noted both visually and by the aspirated Particle Measuring Systems, Inc. 2D-C optical array probe system (see sec. 3). The abundance of needles lasted until about 1236 with a few weak showers accentuated by some graupel particles scattered through the period.

This band might be considered an upper air front; the convergence mechanism appeared to have generated some low altitude CLW, which was partly exploited by the production of needle crystals--some with light rime. The vapor supply decreased across the band, and the latter two-thirds of the band contained only small spikes of CLW.

Immediately after the passage of the previous upper air band with its needle regime, the cloud character changed to stratocumulus showers with diminishing intensity and coverage. Water vapor increased again with intershower minimums after 1700 and at about 1900; major drying occurred after the snow mostly ended at 2100. The vapor signals were spiky in phase with brief bursts in CLW. Some of the liquid pulses were associated in time with graupel showers. An isolated shower at about 1935 was identifiable in the satellite photographs as a shallow small cloud.

23. January 17-19, 1988: Periods SS, SC

During the previous day, a small wave developed along an east-northeasterly to west-southwesterly oriented front in the zonal flow off the California coast. By 2400 between January 16 and 17, the surface circulation had wrapped around a fully formed low though the upper air pattern had only a minor short wave. By evening on January 17, that wave had rapidly intensified into a major cutoff low at the upper levels. The satellite photographs of the storm in the afternoon showed the center of the low to be mostly clear, like the eye of a hurricane. The upper air wave and low center moved southeast from just off the coast to right on it.

In the early morning, the front began to wrap around the southern side of the surface low, entered southern California after sunrise, entered Arizona in the late afternoon, and arrived at Hannagan Meadow during the hour before 2400 (according to the windshift there).

During the evening of January 17, a second surface low formed near Lake Mead, taking over the energy of the storm and leaving the original low to nearly vanish over the north end of Baja California at about 2400. The storm episode started at Hannagan Meadow abruptly just after 1200 on January 17. The Alpine time-lapse photographs showed the 1245 arrival of a dense carpet of altostratus and altocumulus with strong wave-shaped undulations in the cloud base, followed later by snow showers of increasing intensity. Surface winds shifted from west-southwesterly to south-southwesterly and then south-southeasterly with the arrival of this cloud deck. Winds aloft remained strong from the southwest according to the Alpine time-lapse photography and the upper air charts. The radiometer showed a 1235 arrival of abundant water vapor and a first spike of CLW at about 1245. The CLW episode was a major and continuous one, peaking about 1600 and finally ceasing at 1720. The satellite photographs of the afternoon showed a stationary southeast-northwest band of stratiform cloud diagonally across the state and positioned approximately on the Mogollon Rim. In view of the high-speed southwesterly flow aloft, this appeared to be an orographic cloud. There was also a strong clearing northeast of the Mogollon Rim apparently as a result of subsidence. It might also be argued that this cloud band represented a flow of moisture into the storm system from the southeast relative to the storm itself. The second low formed where the cold front met this cloud band in northwest Arizona.

Snowfall from this cloud band was generally light and showery. Graupel was often seen at the ground among a variety of other types. There was also a period of needles indicating low-level moisture.

The arrival of the high prefrontal clouds brought a cessation of the CLW and the start of the major snowfall. Vapor remained high until the passage of the front (with thunder) just before 2400 and then abruptly decreased to dry levels. Snowfall rates generally increased until the very heavy rates occurred just prior to frontal passage. However, rates decreased briefly at about 2030 and 2240, coincident with a return of CLW. (This pattern of inverse relation of CLW amount and snowfall rate has been commonly observed in Arizona and Colorado, but it is not a firm rule.) Snowfall rates were much lighter after frontal passage, but there was no restoration of the CLW through 0200, the approximate time of passage of the rear edge of the high frontal clouds.

After the passage of the frontal band, the pattern changed to convective elements beginning at 0200 on January 18 and lasting to about 1000. Snowfalls were light. CLW was variable in a convective pattern with highest values from about 0350 to 0550. The satellite photographs showed a lumpy pattern of low clouds.

At about 1000, the tall remnants of the clouds about the original low arrived at Hannagan Meadow. Snowfall increased to moderate with the help of aggregates. (Power outages thereafter stopped the collection of all but mechanically or manually recorded data.) The rear of the low passed over Hannagan Meadow at about 1700. The snowfall rates decreased to light intensity for the remainder of the storm.

On January 19, the clouds were mostly stratocumulus instability showers in the rear remnants of the storm system as seen in the satellite and time-lapse photographs. Snowfalls remained light and finally ceased about 1600.

Combining the stratiform and convective portions of this major storm system, the total snowboard measurements were 795 mm snow depth; and the precipitation gauge measurements yielded 62.2 mm of melted water equivalent.

24. January 21-22, 1988: Period SS

This minor episode was a surprise to the field observers and can best be traced to an upper air disturbance in strong northerly flow. In the morning of January 21, a tiny 500-mb low, hardly more than a weak wave, was over southern Montana. This low soon closed and traveled south into northern Mexico. The 700-mb level responded by creating an east-west trough across New Mexico extending into Arizona. Weather map analysts declared a small east-west cold front across central New Mexico and into central Arizona at 0800 on January 21. The front drifted southwards to the Mexican border by 2400 and was declared vanishing at 0800 on January 22.

The satellite photographs showed a northwest-southeast band of stratus forming with an axis northeast of the Four Corners region near sunrise on January 21. The band then drifted south-southwesterly (an unusual direction) with its leading edge arriving at Alpine just after 1400. The time-lapse photographs showed blue sky and transient fair weather cumulus and stratocumulus just prior to the arrival of continuous snow at 1414. By 1835, the snow depth at Alpine was about 50 mm while Hannagan Meadow still had clear skies. The edge of the snowfall was then about 13 km north of Hannagan Meadow. By 2010, about 13 mm more snow had fallen at Alpine while the first crystals began to fall from a clear sky at Hannagan Meadow.

Stars were visible at Hannagan Meadow most of the night, which indicated a very shallow system. The system was so shallow that the nighttime infrared satellite photographs could not distinguish cloud from snow-covered ground in the White Mountains. No CLW was observed above Hannagan Meadow during the passage of this snow period. Crystals there were without rime, and precipitation (melted water equivalent) totaled only 0.20 mm.

The 2D-C probe gave the best detail for this storm period at Hannagan Meadow. Most crystals were stellars, some viewed on edge, and others classified as irregular. A windshift occurred by 2000, changing from southerly to northeasterly with the passage of the weak front. A shower was already in progress when the instrument was turned on at 2132. That shower ended after 2200. The main shower gradually increased after 2300, peaked at about 2400, and reduced to trace intensity after 0150 on January 22. No crystals were observed after 0606. Sunrise was perfectly clear on the Alpine time-lapse photographs for January 22.

This episode does not deserve much attention for cloud seeding possibilities. The episode was so shallow that it appeared to have great difficulty rising up the northeast slopes of the White Mountains. Using a snow density estimate of 1/20 for stellars, Alpine received about 3.2 mm of precipitation compared with a total of 0.2 mm in the gauge at Hannagan Meadow.

25. January 30, 1988: Period SC

This brief episode lasted from about 0300 to 0700. The clouds were apparently orographic stratocumulus, generated as a strong southwesterly flow was forced over the high terrain. The jetstream was above the project area. The upper air flow contained the remnants of a weak short wave, and the moisture may have been the remnants of a Pacific cold front that was erased from the maps upon reaching the coast during the previous day. No snow was observed from this system. Only 2 hours contained small spikes of CLW.

26. January 31, 1988: Period SS

This event is mentioned here, not for cloud seeding potential, but for some insight into the forecasting problem. The period brought no precipitation nor CLW to Hannagan Meadow and therefore would not qualify as an episode by the usual rules. A general flow was being set up that repeatedly brought in tropical air to the Arizona region. On this particular day, there were two jetstream axes--one at the northern Arizona border and the other just south of the southern border. Late in the day, a short wave connecting the two axes passed over Arizona and generated a shield of lumpy cirrostratus ahead of the wave. The time-lapse photographs and field notes confirmed that there was no low- or mid-level moisture with this short wave. The radiometer even showed low vapor amounts.

There were several passages of high cirrus during this general period. The daytime satellite photographs showed these clouds to be thin with no clouds beneath the cirriform shield. At night, the high clouds were sufficiently opaque in the infrared to obscure any clouds below. That was the trap for the local forecasters, who apparently were used to these cirriform passages with no low-level moisture. On January 28, a storm passed over Hawaii that some forecasters called the "Kona storm," which retained its identity all the way to California over the next several days and was associated with its own low-pressure system. This storm was visually attractive, and the attention of the forecasters was likely diverted to it. The forecasters did not detect the next pulse of tropical moisture that entered Arizona, with associated low-level moisture and precipitation in parts of the state.

27. February 1-3, 1988: Periods SS, SC

Ahead of the "Kona storm" was a stream of moisture derived from the tropics and organized by no more than a short wave. There were no surface pressure features or fronts by which to track the stream apart from the satellite photographs. The morning time-lapse photographs from Alpine showed mid-level moisture in the form of altostratus and altocumulus that thickened and began to drop snow at 1228 on February 1 at Hannagan Meadow and at 1230 in the foreground of the Alpine photographs. Thereafter, the snow intensity generally increased but showed some pulsing tendency as bands passed over the area.

Initial snow particles were small and of a type that typically falls from high cold clouds; that is, consistent with an origin in high stratiform layers. Also present were unrimed broadbranch and dendritic crystals both at Hannagan Meadow and Alpine. There was no CLW observed by the radiometer as the high-level snow was efficiently using the CLW.

At about 1830, low-level moisture arrived. The radiometer began detecting CLW, which lasted until 2340. At about the same time, needles became the dominant crystal type. Needles and columns (with a few rare graupel pellets) were the only ice particle types from 1900 (at about 20 L^{-1}) to 2051 (after most of an hour at about 0.3 L^{-1}), indicating that all upper level sources of crystals had ceased to be active. Drizzle drops and a few needles then lasted from 2051 to 2220 at roughly 10 L^{-1}; needles and tiny rime balls lasted to 2301 and then back to needles and drizzle to 2337, all at about 20 L^{-1}. These were all indicators of a shallow, warm, inefficient cloud.

The satellite photographs of the period were carefully examined. The rear edge of the cirriform shield was tracked and found to have passed over Hannagan Meadow at about 1800. A small patch of cirrus then appeared, and the rear edge of this patch passed over Hannagan Meadow at about 2300. From about 1400, a low stratiform deck was observed to linger behind the first main cirriform shield. At 2100, the rear edge of the stratiform deck was far to the west of Hannagan Meadow. There were indications that the rear edge could have suddenly moved to Hannagan Meadow by 2400, but this cloud bank was becoming obscured by the cirrus precursors of the "Kona storm." This low-level cloud bank apparently produced the CLW observed by the radiometer and the drizzle and needle crystals that fell at Hannagan Meadow.

The appearance of CLW after the passage of the rear edge of a cirriform shield has been frequently noted in the Sierra Cooperative Pilot Project observations near Auburn, California. Apparently, cirriform clouds produce an abundance of crystals that fall into any low-level moisture and efficiently consume that moisture to make larger snow particles. When this source of "seed" crystals passes away, then the moisture that is no longer being totally consumed by the snow appears as CLW in the low-level clouds. Such clouds are attractive targets for cloud seeding. In this case, the clouds were producing snow particles; but the concentrations were not sufficient to consume all the CLW.

The return of more intense snow at Hannagan Meadow at 2330 on February 1 and the cessation of the radiometer CLW are taken to indicate the end of the influence of the last storm and the start of the influence of the "Kona storm." The storm had traveled all the way from Hawaii over several days and passed over Arizona farther north than the preceding pulse of tropical moisture. The southern part of this storm was generally convective so that class was given to the storm as seen at Hannagan Meadow. This storm produced the greatest instantaneous readings of CLW and greatest total CLW flux of the 1988 observation season.

The beginnings of the storm had an apparently efficient precipitation process with high (100 L^{-1}) concentrations of needles and columns (warm, low altitude clouds) but no CLW. (Indicated concentrations from the 2D-C probe may be artificially high due to mechanical breakage of crystals hitting the intake of the aspirator.) After 0400, there were small pulses of liquid; and other habits were mixed in as higher altitude clouds began to contribute. At 0823, the snow ceased except for stray particles and resumed after 1000 with needles and columns ceasing to be important after about 1115. Most of the particles thereafter were apparently rimed particles and graupel. Concentrations ranged widely from less than 1 to more than 100 L^{-1}.

The low cloud bases kept Hannagan Meadow and the hilltops normally viewed by the Alpine camera in fog all day. From about 0830 on February 2 to 0745 on February 3, high CLW readings of a highly variable nature generally existed, reflecting the cumuliform nature of the clouds and showers. All day the satellite photographs also showed a persistent subsidence clearing from central Arizona to south-central New Mexico on the downwind side of the Mogollon Rim.

The most intense snowfalls of the storm occurred from 1615 to 1745 on February 2 in advance of an apparent cold front passage. Lightning and thunder were present at Hannagan Meadow between 1700 and 2000. At about that time, there were suggestions of an arc of higher cloud tops from southwestern Colorado to Gallup to Alpine to Tucson and Mexico. The weather map analysts were at that time redefining the cold front positions in the region, and some of the analyses were close to that arc of clouds. The high clouds moved east of the area by 2400, and no thunder was heard thereafter. The showery weather continued through the night but was less intense.

At 0645 on February 3, the weather changed. The snowfall increased to moderate and steady as another cold front (a polar cold front captured by the storm) wrapped around the back side of the low and passed through the Hannagan Meadow area. The CLW essentially ceased as the precipitation process became efficient. The initial precipitation was graupel and rimed particles; but after 0730, precipitation was a steady fall of needles, columns, and needle aggregates lasting with diminishing intensity to 1137. After about 0900, the snow was falling from a bright sky with the sun often able to cast shadows; yet no cloud elements could be resolved. The approximate 1.0 mm h^{-1} precipitation rate with aggregation was apparently falling from thin, shallow clouds.

After some periods of drizzle near 1200, the remainder of the afternoon was of stratocumulus showers dumping a mixture of graupel, needles, and needle aggregates, suggesting ice multiplication in the lower, warmer cloud layers. Liquid water pulses were present from about 1340 to 1640. Snowfall ceased with clearing skies at 1715.

A total of 26.4 mm of precipitation fell from this wet storm. Even so, the overwhelming abundance of unused CLW for about 24 hours indicated that there was a large seeding potential.

28. February 4-5, 1988: Period SS

This storm episode produced the largest cirriform shield of all of the tropical moisture pulses observed at Hannagan Meadow. The surface maps were not analyzed well because most of the approaching activity was southwest of the United States where the data were scarce. The activity may have contained the southwestern remnants of the last polar front to pass the Hannagan Meadow region. This front appeared to be mainly supported by its own upper air short wave that drew a large amount of tropical moisture off of the intertropical convergence zone. There was no recognized low or significant front with the system, which made tracking and forecasting more challenging. Only the rear edge of the system, along the trough axis, maintained a distinct, trackable edge. Eventually, that edge evolved frontal characteristics as the storm began to behave like a frontal wave, rotated, and moved eastwards across the project area.

The satellite and Alpine time-lapse photographs showed that the cirriform precursors of the storm reached the project area about 1500 on February 3 as the previous system was in the final stratocumulus stages. The Alpine photographs showed thick low and middle clouds all morning the next day until the snow started at 1330 on February 4.

At Hannagan Meadow, the snow started at 1218 with cloud base at the treetops; but no CLW was observed up to then nor through 1527 when the electrical power first failed. The radiometer thereafter became essentially inoperable for the remainder of the storm. The 2D-C probe was also operated only from the time the snow started until that first power failure. Thereafter, the power was unreliable for the rest of the storm. (The trouble was later traced to momentary arcing across the site transformer when snow had accumulated on top of the transformer to some depth. The arc burned a clearing in the piled snow until further snowfall filled it in again. The power company offered no remedy for the problem.)

The peak in the snowfall rate occurred at about 2200 after the Hannagan Meadow site was abandoned. The snow ceased by 0500 on February 5. Sunrise time-lapse photographs showed low stratocumulus above the hilltops and the rear cirriform cloud edge; 21.5 mm of precipitation fell from this storm. The skies were then free from significant clouds for 2 weeks.

29. February 17, 1988: Period SC

A strong and narrow 500-mb short wave created this episode out of almost nothing apparent. There was a remnant of a cold front that had become stationary at the U.S.-Mexico border. During the day, the upper air trough created a small low near the Arizona-New Mexico-Mexico corner; but all clouds were tied in orientation to the trough rather than the surface features. The satellite photographs showed the clouds to be in convective bands, confirmed by the tall stratocumulus showers observed in the Alpine photographs.

The Alpine photographs showed virga starting from approaching tall altocumulus clouds at 0900. At 1005, the clouds thickened and the first snow began to obscure the hills. Snow showers then continued until sunset. The radiometer recorded the arrival of CLW at about 0915 with a major pulse starting at 1030. The radiometer then became inoperative for the rest of the storm. The precipitation gauge had its peak during the hour ending 1500. The snow ended there by 2000, giving a storm total of 3.05 mm. The CLW pulses probably continued throughout this episode in the tall cumuliform activity.

30. February 18-19, 1988: Periods SS, SC

Another upper air short wave descended across the West and became a closed circulation passing over Arizona. Though a cold front approached the state with this wave, the short wave vanished before reaching Hannagan Meadow. Thus, there were no surface features, neither front nor low, with this system. The satellite photographs during the night showed structures suggestive of convective bands. The 2D-C probe at Hannagan Meadow recorded three bands of snow during the episode; the third was associated with the central vortex of the upper air low.

The Alpine photographs showed virga arriving at 1554 and snow beginning to obscure the hills at 1620 from an altostratus deck. Sunset soon obscured the view. At sunrise on February 19, a uniform snow fell that ended at 0812. Another shower hit the Alpine area at 0954. However, the third band dumped nearly all of the 6.3 mm of precipitation at Hannagan Meadow between 0500 and 0800.

There was no CLW observed in this system and therefore no seeding potential. The snow crystals were typical of high cold clouds, being small spatial particles with occasional dendrites and plates. The third band of snow yielded concentrations of about 200 L^{-1} with little sign of aggregation. Such concentrations would be expected to eliminate any seeding potential. The lack of CLW, the habits, and the uniform nature of the snowfall within the bands accounted for the choice of SS classification for most of the episode rather than the convective interpretation that might have been indicated from the nighttime infrared satellite photographs. The last 3 hours were called SC as the precipitation became trivial.

31. February 25-27, 1988: Periods SS, SC, SS, SC

This episode was another excursion of tropical moisture into the project area. On February 25, a large cirriform shield entered the state from the southwest but brought neither CLW nor precipitation to Hannagan Meadow. The moisture was driven by an upper air short wave, not any surface low or front. Tracking was possible, as was often the case for such tropical moisture, by satellite photographs only. The moon with a halo was visible at Hannagan Meadow through 2200. About 2400, the cloud band became stretched out and stationary in an easterly-westerly direction across Arizona and New Mexico; and the cirriform shield started to deteriorate. Only then did the weather at Hannagan Meadow respond.

Traces of precipitation fell from this system from about 2300 on February 25 to 0700 on February 26, according to the precipitation gauge. The 2D-C probe recorded snow until 0300 and rain thereafter. The rain mostly ended at 0608 and totally at 0651. The radiometer recorded CLW aloft from 0040 to 0640. Some of that signal could have been slush on the reflector plate and rain aloft, but the proportions cannot be known; the slush was apparently only a minor problem. The surface winds shifted after 0600 from southerly and southeasterly to west-northwesterly. Only 2.1 mm precipitation was recorded from this portion of the episode.

During February 26, some low-level residual moisture from the previous system developed into stratocumulus by 1045. The clouds produced showers with the last remnants leaving the view of the Alpine camera at 1533. Shading from the high clouds of the next part of the episode suppressed further development and marked an end to this convective part.

Another short wave in the upper level flow then brought more tropical moisture to Arizona. Again, the moisture was without any surface low or front. Moderate amounts of CLW (some of which was rain) were observed from 2300 to 0300. Surface precipitation was rain in light amounts totaling 0.8 mm. The stratiform portion of the episode ended leaving a low altostratus cloud visible in the Alpine photographs until 0900.

Residual moisture on the rear (southwest) side of the previous stratiform system developed into cumuliform showers with the solar heating. The radiometer recorded CLW pulses, but the rain was too little to record in the precipitation gauge. Raindrop images were recorded by the 2D-C probe.

32. March 2, 1988: Period SC

This system was a result of a tiny storm system traveling down the California coast and then passing south of Arizona. The storm's cirriform shield was only half the size of the state of Arizona and did not extend to

Hannagan Meadow. Moisture and clouds arrived abruptly after 0830 according to both the radiometer and the Alpine photographs. The latter showed rapid development of wet-looking stratocumulus confirmed by the 0920 arrival of CLW pulses above Hannagan Meadow. Virga began, as shown in the Alpine photographs, about 1224 and reached the ground by 1250. Precipitation was first noted at Hannagan Meadow at 1345 with thunder a few minutes later. A heavy shower started in view at Alpine at 1335. But no significant precipitation was measured at Hannagan Meadow until after 1700. The gauge there recorded 1.1 mm for that shower with a 13-mm depth of snow deposited. That shower marked the end of the CLW at Hannagan Meadow.

33. March 3, 1988: Period SC

A surface cold front was analyzed in a north-south position just east of the Arizona border with New Mexico. That front only indicated a general tendency for cloud development and was not a strong factor in the showers of this episode. The real impulse apparently came as a tiny vorticity center in the upper flow, which produced a small "comma" of taller clouds in the White Mountains. That center was too small to appear on the standard 700- and 500-mb charts within the general trough.

The stratocumulus cloud field in view of Alpine started to grow after 0900 and developed observable CLW above Hannagan Meadow by 1015 and showers in view of Alpine at 1055. The first thunder at Hannagan Meadow was at 1237, and the first graupel shower began at 1253. Graupel showers then occurred all day at both Alpine and Hannagan Meadow. The last CLW was observed as a strong spike at about 2015; the snow soon ceased as well, yielding a precipitation total for the day of 2.85 mm.

34. March 4, 1988: Period SC

A cold front was approaching from the north and eventually reached the area about 2400. The time-lapse photographs showed stratocumulus developing during the day. Some stratocumulus formed turrets, which may have been large enough to have contained some CLW. A note in the log described an instantaneous CLW reading of 0.66 mm during the hour prior to 1410 at Hannagan Meadow, but the radiometer disk data were not recoverable. Most of the stratocumulus clouds were ragged and their tops suppressed. It is unlikely that this episode had significant cloud seeding potential.

35. March 5, 1988: Period MC

By 1300, the cumulus field developed into towering cumulus clouds with first virga at 1355 and precipitation reaching the ground at 1407, according to the Alpine camera. There were then widely scattered showers from these clouds during the rest of the afternoon until 1757. The Hannagan Meadow site was not manned during the cloudy period, and the radiometer data were not recoverable from the disk. Measurable precipitation was not recorded in the gauge. The satellite photographs showed a field of towering cumulus above the entire Mogollon Rim during the afternoon; this field strengthened in response to synoptic conditions associated with a cold front remnant passing to the north of the state. The late afternoon time-lapse photographs especially gave the impression of orographic generation of these clouds in the southwest flow. There was probably sufficient CLW in these clouds for cloud seeding experimentation.

36. March 7-8, 1988: Period SC

A major cold front moved into the area before sunrise but had lost energy; nothing happened in the project area. During March 7, a cumulus field developed over the high ground; a tiny cirrus wave formed to the northwest. These clouds connected over the project area about 1600 when a wall of snow appeared in the Alpine photographs. The observer notes at Hannagan Meadow mentioned graupel as the major component of the snow although dendrites and aggregates were also present at times. Most of the 2.2-mm precipitation from this episode had fallen by 2000. The gauge showed light precipitation contributions until 0500, which must have been from shallow clouds; the night infrared satellite photographs did not reveal these clouds. The data from the radiometer could not be recovered so CLW was not measured. However, the presence of graupel and riming indicated CLW was there at least some of the time.

General Comments

The SS and SC systems dominated the storm episodes. Some pure MS periods were observed in 1987 but none in 1988. Some MC systems occurred in 1987 and one in 1988. All other systems could be traced to upper air short waves (including the tropical moisture periods) and some to surface fronts and lows as well. Several systems came into the area in the SS class and exited in the SC class after the passage of a trough or front. The SS portion of the system often produced the larger precipitation although the SC class may have lasted longer. The precipitation mechanisms and seeding potential may have been different for the two portions.

In 1987, the moisture was spread among several sources, with the offshore Pacific waters appearing to dominate. Most of the moisture for 1988 came from tropical air; those episodes were usually without surface lows or fronts. Sometimes the tropical air was only at the cirrus levels, producing a cirriform shield that shaded the area by day and obscured the area in the nighttime infrared satellite photographs. From the satellite photographs, low- or mid-level moisture could not be confirmed below the cirriform shield at night. Forecasting the arrival of useful lower level moisture and precipitation is difficult for such systems.

The CLW of most interest appeared to always be associated with the lower atmosphere. In major storms, CLW was often associated with high winds near the surface, suggesting low-level orographic uplift over the Mogollon Rim. Precipitation falling from higher clouds then achieved a boost in mass as it fell through the low-level CLW. At other times, only low-level clouds existed, ranging from stratus to stratocumulus to towering cumulus, and often with CLW present. This tendency for the CLW to be associated with the lowest layers of the atmosphere gives some hope to a seeding strategy using a ground-based system of AgI generators. But this also means that the temperatures will be warm, requiring an exotic mix of AgI for ground seeding or possibly aircraft releases of seeding material. Some clouds may be too warm for AgI seeding, and dry ice seeding may be required.

The arrival of the low-level CLW is difficult to forecast; its presence can be determined by the radiometer, and its possible presence may be indicated by establishing the presence of a low cloud base with a lidar or ceilometer. But such are nowcast indicators, not forecast predictors.

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-use organizations, and other concerned groups.