A Review of the Sierra Cooperative Pilot Project

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Abstract

The Sierra Cooperative Pilot Project (SCPP) is an investigation of cloud seeding as a means of increasing winter precipitation on the Sierra Nevada. It is a concerted effort in the development of a physically sound cloud-seeding technology. It involves the use of remote-sensing devices, in situ observations, and the application of a numerical targeting model in randomized seeding experiments. The results have led SCPP scientists to believe that shallow but widespread orographic clouds provide the best opportunity for glaciogenic seeding in the central Sierra Nevada.

1. Introduction

There are indications from statistical analyses of operational and randomized cloud-seeding experiments that, under certain conditions, it is possible to increase precipitation from winter storms over mountainous regions of the western United States by glaciogenic cloud seeding (e.g., Advisory Committee on Weather Control, 1957; National Academy of Science, 1973). However, statistical evidence alone is insufficient to convince many atmospheric scientists of the efficacy of cloud seeding. They require, in addition, firm knowledge of the physical mechanisms responsible for any apparent increase in precipitation.

Evidence of the latter type has been reported by Hobbs (1975) who, using aircraft, radar, and ground microphysical observations, documented the growth and fallout of snowflakes following the glaciogenic seeding of winter clouds over the Cascade Mountains. New types of in situ and remote sensors, coupled with numerical models of hydrometeor growth in air flowing past mountain barriers, show promise that seeding effects can be documented with increasing precision as technology progresses. Table 1 lists several recent or ongoing research programs on winter orographic clouds that are following a scientific approach. This paper describes one of those projects, the Sierra Cooperative Pilot Project (SCPP), to exemplify current trends in research on winter orographic clouds.

2. Historical background

SCPP is an investigation of cloud seeding as a means of modifying precipitation over the Sierra Nevada during the winter. SCPP is conducted by the Department of the Interior, Bureau of Reclamation, in cooperation with the states of California and Nevada, local government agencies, and private firms conducting operational cloud-seeding projects in the same general area.

Operational cloud-seeding projects to increase precipitation and runoff from the Sierra Nevada have existed since 1948. Nearly all of these projects have been based on the hypothesis that the precipitation rate from orographic clouds can be increased by increasing the concentration of ice crystals at temperatures above −20°C. This hypothesis is based on the observation that some orographic clouds contain supercooled liquid water (SLW), which is inefficiently util-

TABLE 1. Recent or ongoing winter orographic research programs with a strong in situ and remote-sensing observational base.

Project	Agency/Funding	Period of operation	Primary study area
COSE (Colorado Orographic Seeding)	Colorado State Univ./NSF	Winter 1979 Fall 1979 Winter 1981/82 Winter 1984/85	Park Range Colorado
CRADP (Colorado River Augmentation Demonstration Program)	Bureau of Reclamation	Winter 1982/83 Winter 1983/84 Winter 1984/85 Ongoing	Grand Mesa, Colorado
Nevada	Desert Research Institute/NOAA	Winter 1983/84 Winter 1984/85 Ongoing	Central Sierra Nevada Walker-Carson Range
SCPP (Sierra Cooperative Pilot Project)	Bureau of Reclamation	Winters 1976/77 through 1984/85 Ongoing	Central Sierra Nevada
Utah	Multiple Agencies/NOAA	Winter 1980/81 Winter 1982/83 Winter 1984/85	Tushar Mountains, Utah

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ized in the natural precipitation process. Artificial ice crystals produced in the presence of this SLW will grow in a few minutes into small snowflakes, thereby utilizing more of the SLW before it evaporates on the downwind side of the mountain. Additional ice crystals can be produced by dropping dry ice pellets or releasing silver iodide (AgI) crystals from aircraft into the clouds upwind of the barrier or by operating AgI generators on the ground. Most operational projects in the Sierra Nevada have used the ground-release method because of its relatively low cost.

Generally, operational programs seed all promising cloud formations with no cases reserved as controls; consequently, it is difficult to evaluate their efficiency. Nevertheless, statistical evaluations of operational cloud-seeding programs in the Sierra Nevada, based on comparisons of streamflow from target and control basins in both seeded and nonseeded years, have indicated increases in runoff of roughly five to 15 percent (Henderson, 1966; Elliott and Lang, 1967).

During the 1960s Pacific Gas and Electric Company conducted randomized seeding experiments near Lake Almanor in the Feather River Basin (Mooney and Lunn, 1969), and the Fresno State College Foundation conducted Project CENSARE (Central Sierra Research) in the Stanislaus and Mokelumne Basins. Both groups concluded that seeding effects depended strongly on wind direction, temperature, atmospheric stability, and other storm characteristics, but their results were not in complete agreement.

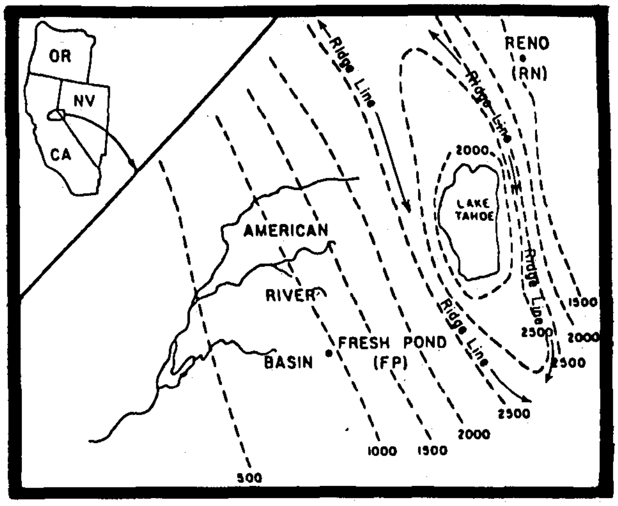

FIG. 1. Map of the Sierra Cooperative Pilot Project area, which is essentially the American River Basin. Smoothed topographic contours are shown as dashed lines and labeled in meters. The total area of the Basin above Folsom is 4220 km^2, of which 1265 km^2 is above 1830 m and receives 90 percent or more of its winter precipitation as snow. The annual runoff averages 3.23 × 10^9 m^3.

3. The design of SCPP

SCPP was conceived in the early 1970s in the hope that a viable seeding technology could be developed to increase precipitation and runoff to alleviate future water problems in California, including salinity problems in the San Joaquin delta. The program officially began in February 1973, with the signing of a cooperative agreement between the state of California and the Bureau of Reclamation. The following three years were taken up with design studies and environmental assessments. During 1974, 21 public meetings were held in California and Nevada to discuss environmental issues and the public's responses were analyzed. It was concluded that, while it was unlikely that the project would harm the environment, environmental studies should be included in the program and the public should be kept informed of SCPP activities.

On the basis of a design study completed in 1976 by MBAssociates, the American River Basin (ARB) was selected to be the primary study area. Figure 1 outlines the location of the ARB and lists some of its important characteristics.

As most of California, including the ARB, has a Mediterranean climate, more than 90 percent of the annual precipita-

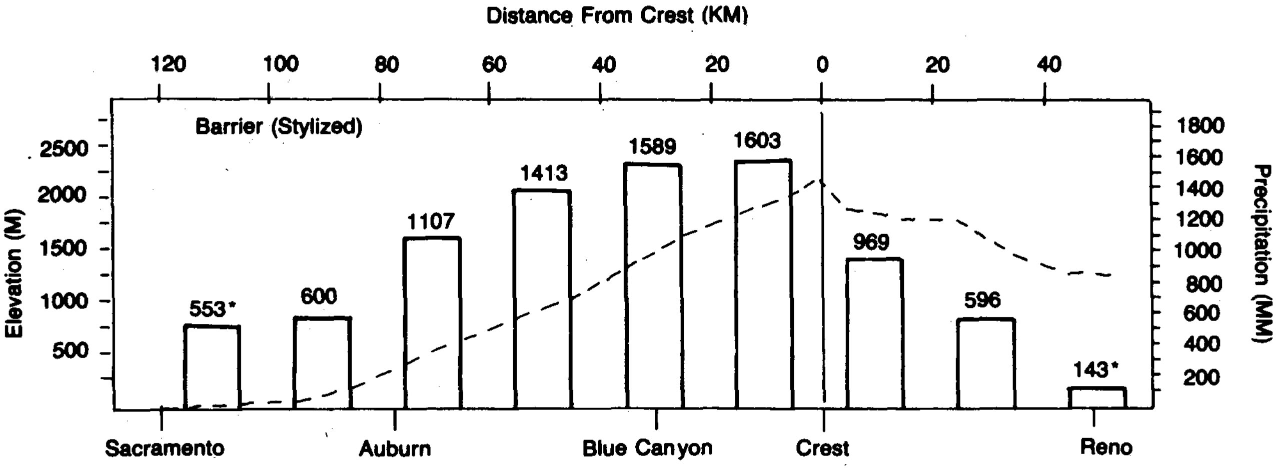

FIG. 2. Barrier traverse plot of winter season (Nov.–Apr.) precipitation totals across the SCPP project area using SCPP precipitation-gauge network. Individual values are network-wide averages based upon 1978/79 through 1983/84 winter-season observations within 20-km distance-from-crest partitions. Values marked by asterisks (*) are from cooperating agencies.

tion in the ARB falls between October and May, while more than 75 percent falls in the colder winter months of November through March. Therefore, SCPP has concentrated on winter cloud systems, with intensive field observations taken from early January through March.

The storms affecting this region usually move in from the Pacific Ocean, with the associated air masses having had long residence times over the ocean. The freezing level usually is between 1000 m and 3000 m. The warmer storms usually move in from the southwest. Colder storms, with the freezing level occasionally as low as 300 m, come from the Gulf of Alaska. These storms often stagnate just off the coast, bringing showery weather for several days.

The average annual precipitation from the Sacramento Valley floor to the Sierra Nevada crest and beyond Lake Tahoe is shown in Fig. 2. As one proceeds eastward, the precipitation initially increases with elevation on the west or upwind side of the Sierra Nevada, but shows little change from Blue Canyon to the crest. Then it decreases rapidly downwind of the crest.

The specific objectives in designing SCPP were to identify the conditions under which cloud seeding causes precipitation increases or decreases in the Sierra Nevada and to estimate the magnitude of these changes. To achieve these objectives a network of in situ measuring systems, as well as weather radars and aircraft, have been put into the field. Because cloud-seeding studies deal in space and time scales varying from millimeters and seconds (sampling changes in snow crystals) to thousands of kilometers and days (monitoring storm systems moving inland from the Pacific Ocean), a varied mix of equipment has been required. Table 2 gives a complete list of equipment used in SCPP at one time or another and their applications.

Most measurement systems employed have been concentrated in or near the ARB as shown on Fig. 3 (top), which locates the sites with major equipment installations. An elevation transect across the Sierra Nevada is shown as Fig. 3 (bottom).

Data collection for SCPP began during the winter of 1976/77. The SCPP field office was set up at Auburn, California in September 1977. SCPP has been in the field each winter since then with the exception of 1980/81, which was a stand-down year for analysis of the data collected during the three preceding years. Cloud-seeding experiments have been conducted on SCPP since the winter of 1977/78, but on a limited scale and with close attention given to suspension criteria that were designed to prevent seeding during hazardous weather situations.

TABLE 2. Equipment and instrumentation used on SCPP, 1976–85.

Equipment	Purpose
PRECIPITATION GAUGES	
Telemetered Weighing Gauge	Real-time precipitation intensity
Recording Belfort Weighing Gauge	Document precipitation intensity
Heated Tipping Bucket Gauge	Precipitation intensity
Disdrometer	Droplet spectra
Various wind, temperature, humidity, and pressure sensors	Real-time and recorded to determine character of storm system
Rawinsonde Station (4)	Measure the vertical profile of temperature, humidity, wind
Pibal	Determine the low-level wind profile
SNOW CRYSTAL SAMPLING	
Photo-Replicator	Determine habit and rime of snow crystals
Photomicrographs	Determine habit and rime of snow crystals
Aspirated Two-dimensional Laser Probe	Continuous observations of crystal concentration and size
AEROSOL AND TRACER	
NCAR Ice-nucleous Counter	Nucleation efficiency of AgI generators
High Volume Samplers	Collects AgI particles and determine concentration
Snow Samplers (manual)	Concentration of trace elements in snow including silver
SF_6 Detector	Measure concentration and movement in trace gas within cloud
AIRCRAFT	
CLOUD PHYSICS	
University of Wash. B-23	Transport and diffusion Precipitation physics
University of Wyoming King Air	Transport and diffusion Kinematic studies Precipitation physics
SEEDER/TRACER	
University of Wash. Cessna 207	Release tracer material Observe cloud top
Aero Systems, Inc. Aero Commander	Dispense dry ice and silver iodide Release radar targets for wind studies Physical observations in cloud
University of North Dakota Piper Cheyenne II	Dispense dry ice Silver iodide Precipitation physics
REMOTE SENSING	
Acoustic Sounders (2)	Monitor stability, inversions, turbulence in boundary layer
National Weather Service (Sacramento) WSR-57 S-band Weather Radar	Monitor precipitation and organization of storm
Skywater C-band Weather Radar	Monitor and record precipitation patterns
NCAR C-band Doppler Radar	Monitor precipitation intensity and motion within clouds
NOAA X-band Doppler Radar	
Microwave Radiometer	Passive detector of liquid water and vapor
K-band Radar	Monitor depth of precipitating clouds
GOES Weather Satellite	Monitor and record satellite observed cloud patterns

4. Special equipment

a. Aircraft

The project aircraft have been maintained at McClellan AFB (near Sacramento) during each of the intensive field seasons conducted since 1976. In most winters, a seeder aircraft and a cloud-physics aircraft have been used. Both are high-performance, twin-engine planes capable of extended flight in severe wind and icing conditions. The seeder aircraft is capable of seeding clouds by dispensing dry-ice pellets from a

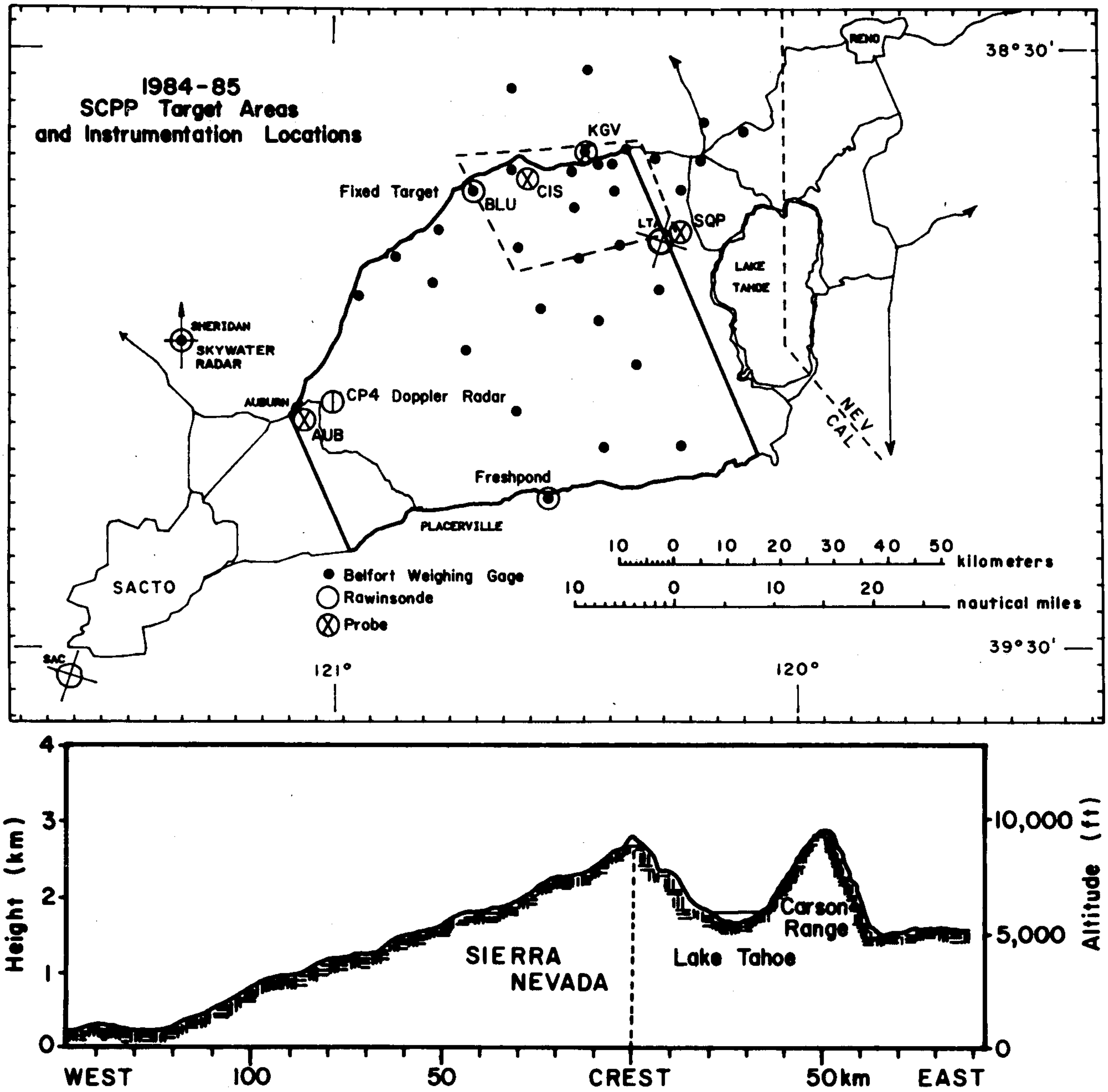

FIG. 3. (top) Layout of SCPP instrumentation for the 1984/85 field season and (bottom) elevation transect over the American River Basin.

hopper or by dropping burning pyrotechnic flares containing AgI. It carries a limited set of meteorological instruments. The cloud-physics aircraft is state of the art. The present aircraft, a Super-King Air 200T, is operated by the University of Wyoming. It carries a number of sophisticated laser probes capable of counting, sizing, and imaging cloud and precipitation particles as it performs its mission. Both aircraft are flying laboratories in that the on-board computers provide the on-board scientists with data for real-time guidance of field operations; the data are recorded on magnetic tape. A computer on the ground provides processed data overnight for quality control and in-depth analyses. The computer on board the cloud-physics aircraft is used to quantify the seedability of cloud formations and to make repeated penetrations of a seeded volume of air, thereby allowing the growth and fallout of ice particles produced by seeding to be monitored.

b. Rawinsondes

Vertical profiles of wind, temperature, and moisture are derived from rawinsonde stations at Sheridan (SHR), Blue Canyon (BLU), Kingvale (KGV), and Freshpond (FSP) at three-hour intervals.

c. Radar

The Skywater C-band weather radar set located near Sheridan is used to track precipitation areas and to monitor project-aircraft positions. A C-Band Doppler radar has been made available by the National Center for Atmospheric Research about every other year to measure both the intensity and motions of precipitation particles for the purpose of estimating local precipitation and wind variations. The K-band radar,[3] first operated at Kingvale in 1983/84 by the Desert Research Institute, is used mainly to determine the vertical extent of clouds passing over the crest.

Precipitation measurements are made by a network of recording precipitation gauges. The number of gauges has varied from 20 to 60. Some of the gauges are in remote areas and require servicing by helicopter. The snowfall at the ground is studied also by the Ground Microphysics Laboratory (GML) (Humphries, 1985). The GML consists of a camper truck equipped with instruments for counting and measuring snow crystals and for studying their shapes. In addition, snow samples sometimes are collected for analysis of trace impurities, including silver, to note if changes in precipitation rate can be related to changes in silver content in the snow.

A new addition to the SCPP instrumentation list is a dual-channel microwave radiometer. This instrument, which has been operated at high elevations in the ARB for the past two seasons, will be discussed in the following section.

5. Physical observations within Sierra Nevada storms

a. Supercooled liquid water and its relation to Sierra Nevada meteorology

SLW is necessary if glaciogenic seeding is to affect precipitation. Therefore, SCPP scientists have given close attention to the problem of finding and measuring SLW and relating its occurrence to the meteorological setting.

The principal tools for finding SLW in the early years of SCPP were the optical probes mounted on the cloud-physics airplane. These probes recorded sizes and concentrations of cloud and precipitation particles. This information combined with radar echo patterns could then be used to relate the presence of SLW to stages in a storm's life cycle (Heggli et al., 1983).

The first few winters of exploration inside deep storm clouds over the ARB showed SLW to be less abundant than had been expected. The highest concentrations of SLW measured by aircraft were found in cumulus clouds forming about 30 to 65 km upwind of the crest, i.e., over the foothills, behind eastward-moving storms (Rangno et al., 1977). However, frequent observations at the surface of rimed snowflakes falling from the shallow orographic cloud remaining on the barrier after the deep orographically enhanced storm clouds moved through provided an indication that a seeding potential might exist in the shallow orographic clouds as well.

The instrument that appears to provide the most useful measurement of liquid water is a dual-channel microwave radiometer (Hogg et al., 1983). Such an instrument was operated on SCPP in the 1979/80 winter program and again in 1980/81 (Snider and Rottner, 1982). In both seasons, the instrument was located below the snowline so it was not clear how much, if any, of the observed liquid water was supercooled. During March 1983, a dual-wavelength scanning radiometer was operated at Blue Canyon (1585 m). Considerable information was collected on the presence and amount of SLW within the larger storm systems. During the 1983/84 season the radiometer was operated for three months at Kingvale (1980 m) (Figure 3, bottom), which is above the snow line in nearly all storms, so that the liquid water detected had to be supercooled. With the radiometer at Kingvale, the monitoring of SLW can be continuous throughout a storm instead of being confined to a single aircraft flight, which provides only limited, discrete samples within a restricted vertical air space. In combination, the radiometer and K-band radar data from Kingvale, the cloud-physics aircraft data, and the vertical temperature and humidity measurements (from the rawinsondes at Kingvale, Blue Canyon, and Sheridan) have begun to clarify when a potential exists for positive seeding effects.

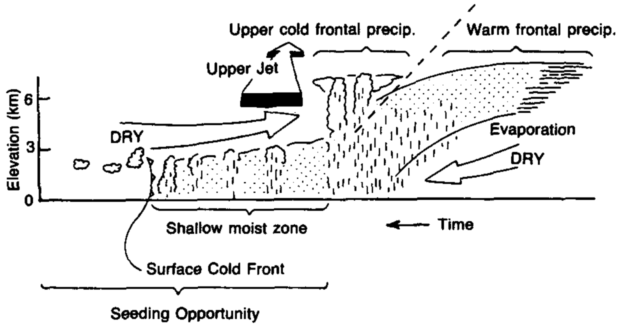

FIG. 4. Cross section through a split front. Stippled areas denote relative humidities above 90 percent. Most seedable regions determined from radiometric and aircraft observations within the storm are annotated. (After Browning and Monk, 1982).

The cross sections of some storms passing the Sierra Nevada (Fig. 4) have been found to resemble those of certain storms over the Pacific Northwest (Hobbs, 1978) and the British Isles (Browning and Monk, 1982). SLW often develops behind the upper cold front (prefrontal cold surge) as the cloud top lowers. (Heggli and Reynolds, 1985). The residual clouds, which are generated by moist air flowing over the mountains, are purely orographic. Preliminary studies of rawinsonde data over the barrier show that the water saturated layers in these clouds, and thus the bulk of the SLW, generally lie below the −10°C level. The liquid water observed in these clouds sometimes causes extreme airframe icing and constitutes a hazard to flight operations (Sand et al., 1984).

Once the surface cold front passes the barrier, the clouds become more convective. Convective cells form near the foothills and move upslope. These newly formed cells often contain little ice and account for the relative abundance of SLW over the foothills.

Presently, it is believed that the shallow orographic clouds provide the best potential for precipitation increases through cloud seeding. This is because the SLW in them is long lasting

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[3] K-band denotes 9 mm wavelength radar.

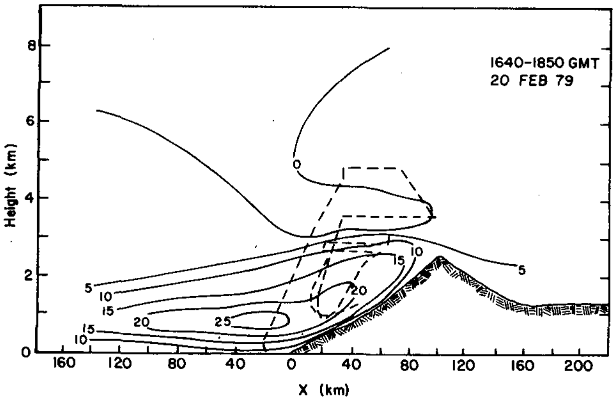

FIG. 5. Horizontal wind components (m • s^{-1}) parallel to the barrier on 20 February 1979 under stable orographic flow. Dashed line shows flight path of cloud-physics aircraft. Wind flow is into the plane of the paper (from Parish, 1982).

TABLE 3. Number of days between 1 January and 31 March meeting suspension criteria.

Year	No. of days
1979/80[a]	23
1980/81	stand-down
1981/82	15
1982/83	49[b]
1983/84	31[c]
1984/85	2

[a] Used only river and reservoir criteria (no snowpack).

[b] From 26 February through the end of the observational period project in suspension because of excess snowpack water equivalent.

[c] All of January under suspension due to high water level of Lake Tahoe.

and distributed over a large area, providing the opportunity to target the seeding effects to the upper elevations of the ARB as additional snowfall for spring runoff. This finding is in agreement with those of other programs that have been conducted over mountain barriers (Ludlam, 1955; Mielke et al., 1970; Hobbs, 1975; Rauber and Grant, 1986). Seeding opportunities in orographic clouds can be forecast through the use of animated satellite infrared imagery sensitive to cloud-top temperature changes (Reynolds et al., 1978), which allows the operational lead time necessary to ready the aircraft and other equipment for a seeding mission. On the other hand, SLW in convective clouds tends to be confined to newly formed convective cells, where its lifetime tends to be short, say 10 to 15 minutes.

b. Air motions in Sierra Nevada storms

Winds over mountains are complicated. However, they must be documented and understood if an effective and reliable seeding strategy is to be developed.

Observations at the ground reveal little about winds aloft. Wind observations on SCPP have been derived mostly from the navigation systems of the research aircraft and from rawinsonde stations distributed across the barrier. During four winters additional detailed wind data were obtained from Doppler radar sets operated by the National Center for Atmospheric Research and by the National Oceanic and Atmospheric Administration.

The most interesting finding so far is that a barrier jet occurs over the foothills during many winter storms. Although low-level jets have been observed immediately in advance of cold fronts (Hobbs, 1978), numerical simulations of the SCPP situation have indicated a strong topographic influence on low-level winds well in advance of the approaching cold front (Parish, 1982). The barrier jet blows from the southeast toward the northwest parallel to the mountain crest (Fig. 5). It can be thought of as a flat ribbon about 1 km deep with its center about 1 km above the terrain, and extending from the valley floor well up toward the crest (~100 km width). Speeds up to 25 m • s^{-1} are common; in some cases the barrier jet has been observed to exceed 40 m • s^{-1}.

The barrier jet occurs when a large-scale low-level flow of stable air impinges on a two-dimensional mountain barrier of significant height. It can occur in both the deep and shallow orographic clouds and is a significant factor in attempts to target seeding effects.

6. Suspension criteria

During the first years of SCPP, detailed studies were conducted to develop a set of criteria to be used for suspending seeding operations during potentially hazardous situations. Even though actual precipitation increases might be quite small, the Bureau of Reclamation wished to avoid even the appearance of contributing to any weather-related losses.

TABLE 4. Blue Canyon precipitation total for 12-month period ending 30 June and ranking for the 85-year record. The annual average is 1717 mm (67.58 in.).

	Precipitation			
Year	mm	in	Rank	Comment
1977	685	26.98	85th	Driest year on record.
1978	2232	87.87	14th	
1979	1527	60.10	45th	
1980	2179	85.77	16th	
1981	1074	42.30	70th	No field operations.
1982	2936	115.60	1st	Wettest year on record.
1983	2747	108.15	2nd	Record snowpack water content.
1984	2075	81.71	19th	Fourth wettest July–Dec on record, driest Jan on record.

In 1980 the preliminary criteria were modified to include excess snowpack accumulation, rain-induced winter flooding, severe weather, and other special circumstances. The excess snowpack water equivalent refers to excesses above a predetermined threshold value that changes daily through the winter months. The thresholds were established using historical data to determine at what point one should anticipate weather-related problems. Flooding refers to anomalous inflows or releases at Folsom Reservoir, which is on the American River near the Sierra Nevada foothills. Severe weather includes hailstorms, lightning, and the like. Special circumstances are conditions that might be hazardous to the public or project personnel, such as avalanche warnings for the Sierra Nevada, snowfalls at low elevations, and high water in Lake Tahoe threatening property owners. Specifics of these criteria are documented each year in the SCPP Operations Plan.

Suspensions have had a serious impact on seeding operations, mostly because of the wet conditions during 1981/82 through early 1983/84 (Table 3). Table 4 ranks each of the last eight years of annual precipitation at Blue Canyon, California, against all years from 1899/1900 to 1983/84; it indicates that the precipitation regime in the Sierra Nevada during the SCPP years has been anomalous.

7. Seeding studies

Despite the frequent suspensions, some seeding experiments have been conducted. They have generated a considerable amount of knowledge about the physical processes involved in natural and augmented precipitation development. Table 5 lists all seeding operations conducted on SCPP since its inception.

TABLE 5. SCPP seeding operations. No seeding was done in the winters of 1976/77 and 1977/78.

Date	Seed Type	Cloud Type
31 Jan 1979	CO_2	Stratus
14 Feb	CO_2	Conv. cells
16 Feb	CO_2	Conv. cells
18 Feb	AgI	Band
20 Feb	CO_2	Orographic
28 Feb	AgI, CO_2 randomized	Orographic
29 Feb	AgI, CO_2 randomized	Orographic
15 Mar	AgI, CO_2	Orographic
17 Mar	AgI randomized	Convective complex
18 Mar	AgI randomized	Convective complex
21 Mar	CO_2, AgI	Conv. cells
22 Mar	AgI	Orographic
08 Jan 1980	AgI	Stratus
10 Jan	Placebo, randomized	Conv. cells
02 Feb	AgI	Orographic
14 Feb	AgI	Orographic
27 Feb	AgI	Orographic
03 Mar	AgI, CO_2, randomized	Orographic
18 Jan 1982	CO_2	Conv. cells
19 Jan	CO_2	Conv. cells
28 Jan	Placebo, randomized	Conv. cells
09 Feb	AgI	Orographic
26 Feb	CO_2, AgI	Orographic
02 Mar	CO_2 randomized	Conv. cells
03 Mar	CO_2 randomized	Conv. cells
10 Mar	AgI	Orographic
15 Mar	CO_2 randomized	Conv. cells
16 Mar	Placebo, randomized	Conv. cells
17 Mar	CO_2	Orographic
27 Mar	CO_2	Conv. cells
30 Mar	CO_2, AgI	Orographic
18 Jan 1983	CO_2	Orographic
19 Jan	CO_2 randomized	Conv. cells
05 Feb	CO_2	Orographic
12 Feb	CO_2	Orographic
18 Feb	CO_2 randomized	Conv. cells
09 Feb 1984	CO_2	Conv. cells
13 Feb	CO_2	Orographic
15 Feb	CO_2	Orographic
16 Feb	CO_2	Conv. cells
21 Feb	CO_2	Orographic
24 Feb	CO_2	Orographic
13 Mar	CO_2	Orographic
14 Mar	CO_2	Orographic
15 Mar	Placebo, randomized	Conv. cells
31 Mar	CO_2	Orographic
26 Jan 1985	CO_2	Orographic
28 Jan	CO_2 randomized	Orographic
02 Feb	CO_2 randomized	Orographic
07 Feb	Placebo, randomized	Orographic
02 Mar	CO_2	Conv. cells
04 Mar	AgI randomized	Orographic
07 Mar	CO_2, AgI	Conv. cells
11 Mar	CO_2	Conv. cells
24 Mar	Placebo, randomized	Orographic
26 Mar	Placebo, randomized	Orographic
27 Mar	CO_2, randomized	Conv. cells
28 Mar	CO_2	Conv. cells

During the 1977/78 winter season, both ground and aerial releases of AgI and tracers were performed to identify conditions leading to the optimum transport and diffusion of these materials. Although performed during fair weather for flight-safety reasons, the aircraft surveys using ice-nucleus counters and millipore filters showed that seeding material from ground generators was not reaching sufficient heights for adequate nucleation nor did the material diffuse adequately to treat large volumes of cloud. During stormy conditions, upward transport might be better; however, targeting the ground-generator plumes would be more difficult, especially with a barrier jet present. Therefore, it was decided to use aerial seeding to ensure that an adequate supply of seeding material was delivered to the appropriate locations at the desired times.

In 1978/79, calibration seeding trials were conducted in which particular clouds or cloud groups were treated with specified amounts of either dry ice or AgI. Both stable orographic clouds and isolated convective clouds were treated. These seeding trials continued through the 1979/80 winter season. As mentioned earlier, 1980/81 had no field operation.

a. Floating-target experiment

The general conclusion from the trials through 1979 was that the convective clouds which often develop in post-frontal situations appeared to have a greater seeding potential than any other cloud type observed in the SCPP. This conclusion was reached because 1) in-cloud microphysical evidence shows more water and less ice in this cloud type, 2) surface observations of crystal type and degree of riming indicate a similar trend, and 3) data in hand showed rapid dispersion of seeding materials and uncomplicated fall-out trajectories compared to the other clouds. It should be noted that this same conclusion was reached after only one season of physical studies by the University of Washington B-23 aircraft during the drought year of 1976/77 (Rango et al., 1977).

A decision was made in 1981 that a randomized "exploratory" (Flueck, 1982) experiment would be initiated on cellular convection. This experiment, sometimes called SCPP-1, was to go on while research continued on other cloud types to serve as the basis for additional randomized experiments. A design for a floating-target experiment was begun in the summer of 1981 (Bureau of Reclamation, 1983). After preliminary trials during the winter of 1981/82, the floating-target experiment began officially in 1982/83.

The floating-target experiment was designed to investigate the effects of airborne delivery of dry-ice pellets or AgI pyrotechnics to convective clouds over a large portion of the American-Truckee-Tahoe river basins. Clouds are treated along 37-km lines oriented parallel to the Sierra Nevada. The seeding rate is now set at 0.4 $kg \cdot m^{-1}$ for CO_2 or one 20-gm flare per 10 seconds of flight time. A classification run is made by the cloud-physics aircraft prior to seeding to determine the relative seedability of the clouds. The clouds are classified A, B, or C, with A surmised to be the most seedable and C the least seedable. Each experimental unit lasts 30 minutes. The basic seeding hypothesis includes the creation of more ice crystals in cloud, formation of more precipitation particles, and changes in radar characteristics. Increases in the amount and coverage of precipitation on the ground from this experiment are expected to be negligible. This expectation is due to the analysis of both aircraft and radar data from nonrandomized seeding experiments showing that, for 30-minute treatment periods, any additional precipitation falling would be below the level of detectability of the SCPP precipitation gauges. Primary seeding-response variables used in the statistical analysis range from ice-crystal concentrations soon after seeding (three minutes) to changes in the radar-echo coverage. The ability to distinguish seed from no-seed cases is greatest from a few minutes to tens of minutes after seeding, but decreases as the associated precipitation approaches the ground.

Because of suspended operations, lack of adequate cloud conditions, and changes in seeding priorities, only three randomized events in the floating-target experiment have been performed over the last two years. Nevertheless, results from calibration trials and these randomized events indicate that seeding signatures in these convective clouds are detectable by both aircraft instruments and radar (Huggins and Rodi, 1985). Many of these clouds have lifetimes too short for developing additional precipitation from seeding. This is mainly due to the mixing of dry air into the cloud as it tries to grow in the post-storm environment. Some cumulus clouds last long enough to develop augmented precipitation from seeding but it is difficult to predict which of the many clouds that form will in fact do so. The impact of these results on future convective cloud studies will be discussed in a later section.

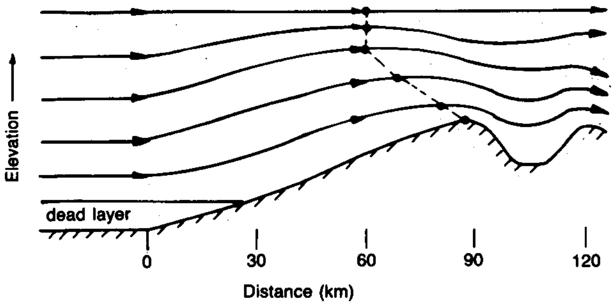

FIG. 6. Schematic mass-flow channels shown normal to barrier as produced by the GUIDE model flow routine. Upwind sounding is extrapolated through these channels. Under stable conditions, crest of flow shown to slope back aloft and blocked flow is shown as dead layer.

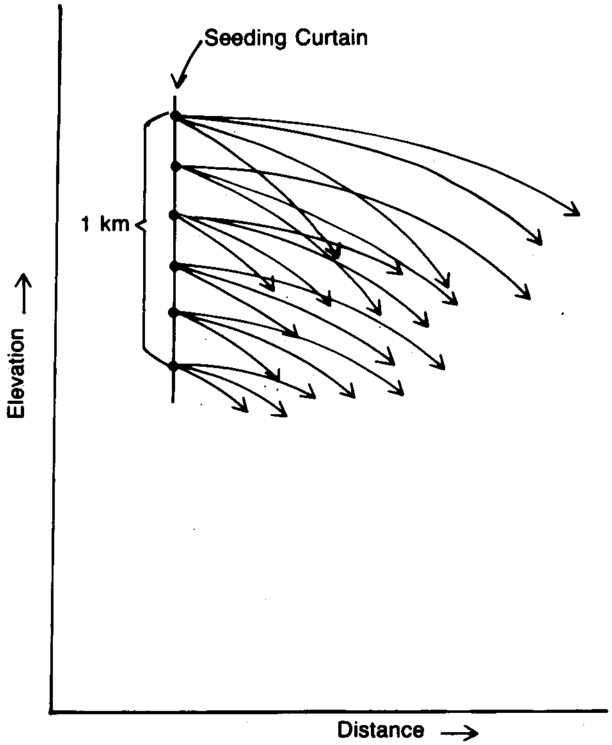

FIG. 7. Symbolic depiction of trajectories resulting from simultaneous initiation (from six levels) of six packets of crystals where each packet contains several crystals which evolve with differing time-dependent fall-speed functions.

b. Fixed-target experiment

Calibration seeding trials have been conducted on the more-stable orographic clouds also. In some cases seeding signatures were detected by the cloud-physics aircraft (Stewart and Marwitz, 1982) and possibly by the GML, indicating that precipitation at the ground might also have been affected.

A randomized fixed-target experiment to test effects of aerial seeding on orographic clouds was initiated in 1984/85. The fixed target has been set up near the upper reaches of the ARB (Fig. 3, top). Within this target are 11 precipitation gauges along with the Kingvale site, where both remote-sensing and direct-observation platforms (GML) are operated to quantify the effects of seeding. The Auburn forecast office also has access to the four remote PROBE (Portable Remote Observation of the Environment) weather stations, whose data are telemetered via GOES (Geostationery Operational

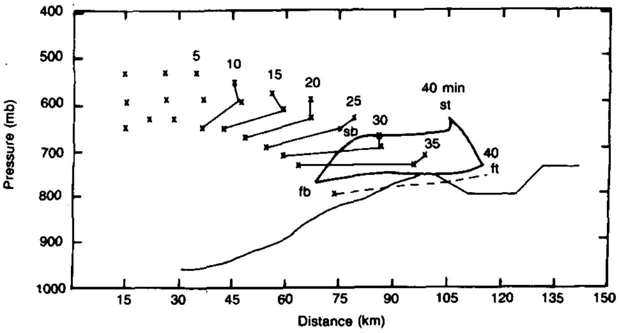

FIG. 8. X-Z plot of initially vertical seeding curtain showing position at five-minute intervals in a strongly sheared environment. One time-dependent fall-speed function used for this depiction. Envelope encloses crystals using method described in Fig. 7. st = slowest crystal from top, ft = fastest from top, sb = slowest from bottom, fb = fastest from bottom.

Environmental Satellite) satellite, animated GOES satellite imagery, color radar imagery, and telemetered real-time radiometer data. All of this information is used to "nowcast" when seedable conditions will exist.

Following Hobbs (1975), a computer program is run in real time to target the seeding effects to the desired location. The program has two main parts. The first part is a quasi-empirical airflow model that conceptually incorporates the basic features of more-theoretical simulations. The model assumes the terrain to be a long two-dimensional ridge. At each grid point, the flow component normal to the barrier is computed on the basis of steady-state flow in constant-mass flow channels, while an empirical location-dependent formula is used to specify the component parallel to the ridge. Model-input requirements consist of the latest rawinsonde data and a wind profile obtained by the cloud-physics aircraft during its climb from McClellan. The second part of the program is a trajectory-computation routine which uses the model wind field, the sounding-temperature profile, and a time-dependent crystal-growth and fall-speed subroutine. Schematics illustrating both the flow model and trajectory model are given as Figs. 6, 7, 8, and 9.

By trial and error the seeding line is adjusted to make the artificial snowflakes fall near the Kingvale site. The so-called Q-point (seeding-line midpoint) and orientation of the 37-km-long track are relayed back to the aircraft within five minutes of receipt of the aircraft wind information. Treatment involves a 1/3 CO_2, 1/3 AgI, 1/3 placebo randomization scheme if SLW is found above the −8°C level, i.e., at lower temperatures; and 1/2 CO_2, 1/2 placebo if the SLW is limited to regions below this level. The seeder aircraft dispenses the seeding material for two hours. The cloud-physics aircraft flies perpendicular to the seeding track within the anticipated seeding plumes to monitor the growth of the artificially produced ice and the depletion of the liquid water. Data collected at Kingvale are averaged over the entire two hours that treatment effects are calculated to be over the site. The aircraft, the Skywater radar, and the Kingvale instrumentation constitute the primary seeding-response mea-

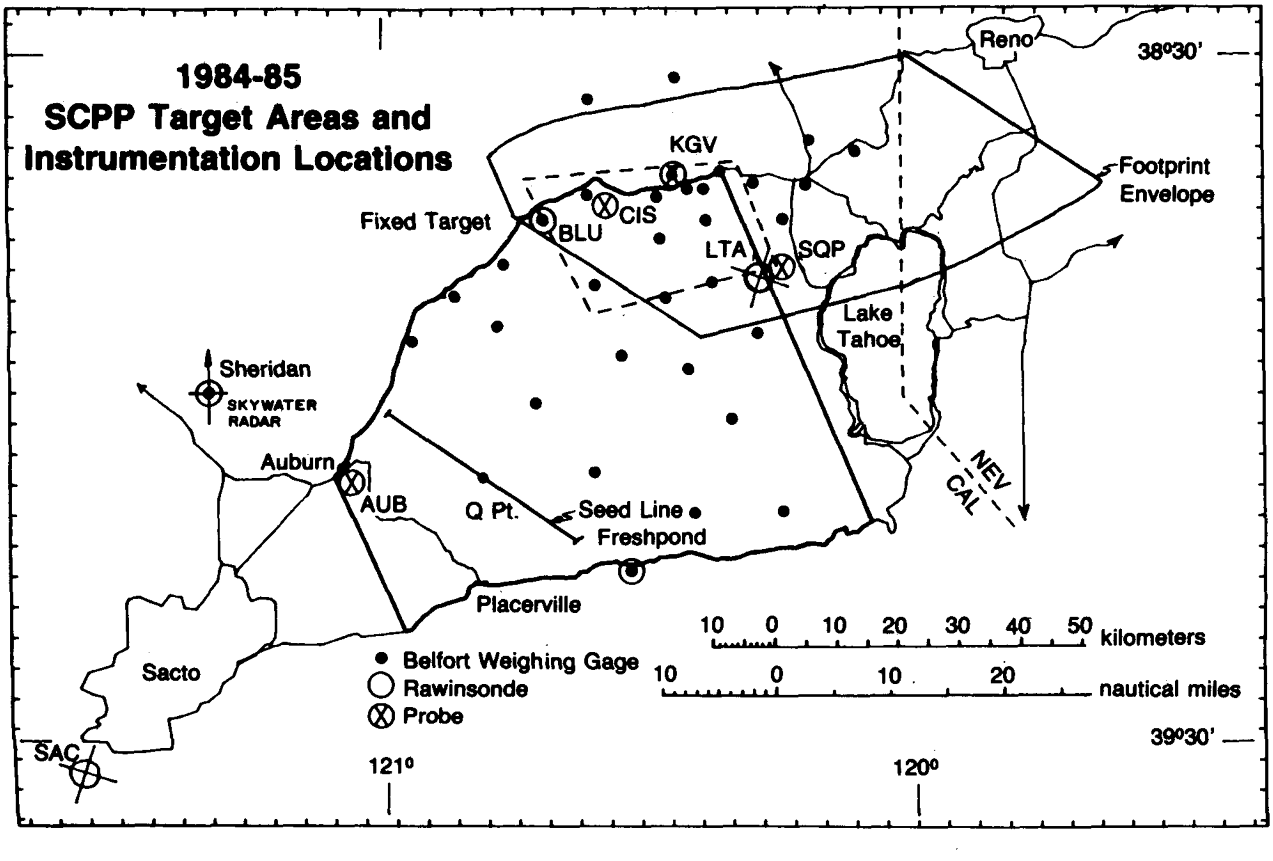

FIG. 9. From seed line shown, fallout footprint from spectra of fall speeds as defined in Fig. 7.

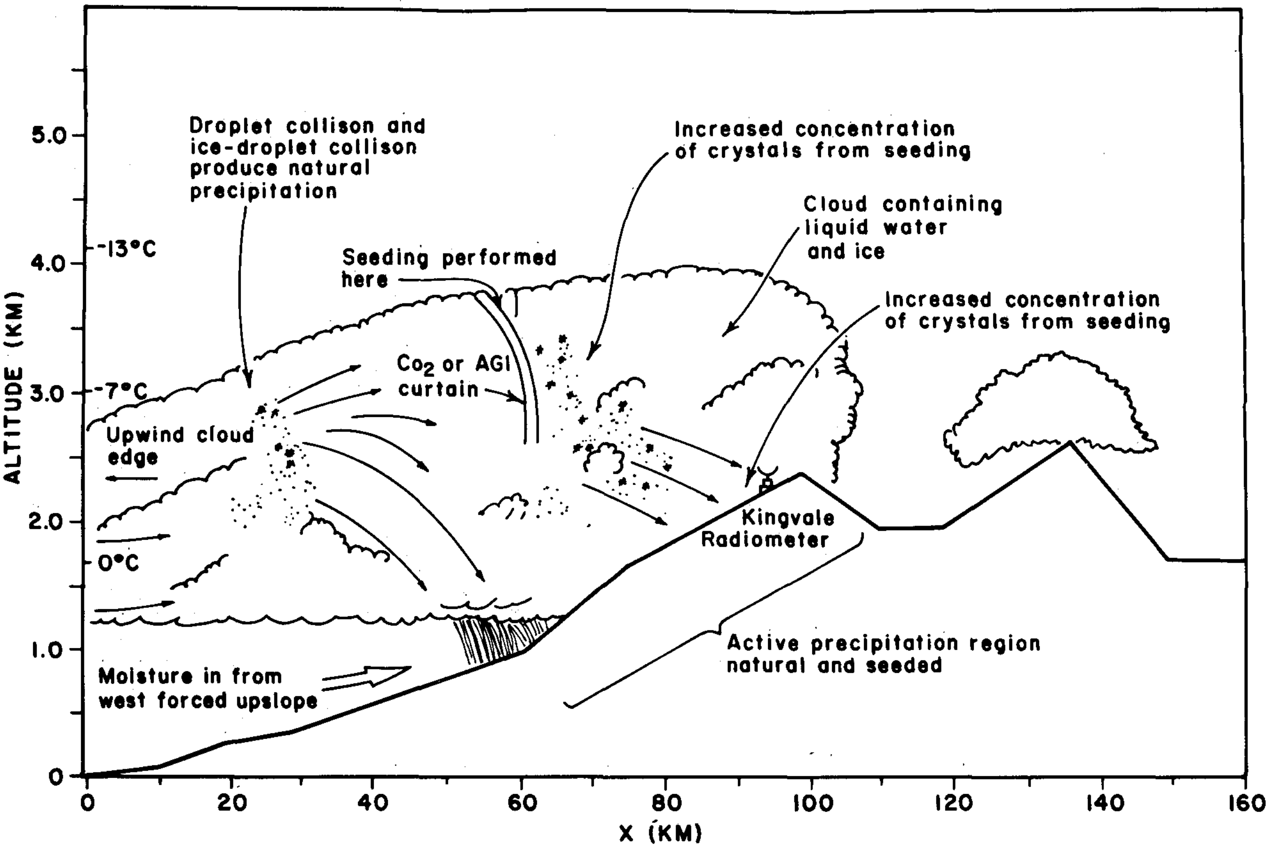

FIG. 10. Illustration of the cloud conditions giving rise to optimum seeding potential. Seeding strategy is to take advantage of liquid water through addition of more ice to lower crystal trajectories, sweep out the liquid, and minimize loss of both liquid and ice escaping the barrier.

surements. Data from other project instruments are used to stratify the day's meteorological activity.

An experimental unit may be called between 5 A.M. and 10 P.M. Monday through Saturday when observations indicate the proper meteorological conditions exist (see also Section 7). It is possible that more than one mission can be called on a given day, but not more than two. In a normal year as many as 10 to 12 randomized cases may be expected. Seven randomized fixed-target cases were completed in 1984/85, which was a year when less than half the normal number of precipitation days occurred. It is not expected that statistically significant results will be obtainable during this three-year randomized experiment due to the large number of seed/no-seed samples required (>200 seed/no-seed cases required for the ground-measured response variables assuming a 10 percent effect). However, case studies using detailed physical analyses should provide evidence of the effects seeding is having on the precipitation process.

8. Current status of SCPP

From the results presented and detailed studies from the past two field seasons a general description of a storm period having potential for precipitation increases through glaciogenic seeding can be given. This storm period is one in which a portion of the available condensate is transported over the barrier and generally lost to the precipitation process by evaporation. Condensate is lost in the form of supercooled droplets and of small ice crystals generated naturally on the upwind side of the barrier which do not grow large enough to fall out. Normally, about twice as much condensate is lost in the form of ice swept over the barrier as is lost in the form of liquid water. Thus, an appropriate seeding strategy is one which causes the liquid water to convert to ice earlier and further upwind, so that the crystals can grow larger and fall out on the upwind barrier. Calculations by Rodi et al. (1985) using actual cloud conditions measured during SCPP seeding operations show that most particles growing in the presence of SLW will obtain a fall speed of from 1 to 1.5 $\mathrm{m \cdot sec^{-1}}$ after about 40 minutes, allowing them to fall 2 km (normal depth of cloud). Seeding is normally done between −10 and −15°C. Thus a nominal value of −12°C was used to initiate these growth calculations. Figure 10 illustrates how these processes might take place over the American River Basin.

It is planned to continue the present series of intensive field seasons through 1987. Following the current series of intensive field seasons a two-year analysis effort will be performed. This will allow for a review of almost 10 years of physical observations and a synthesis of the results from both randomized seeding experiments. The projected benefits from a full-scale operational program will be assessed and recommendations for future applications will be provided.

Information developed in SCPP to date is already being applied to planned or existing seeding programs in both California and Nevada.

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References

Advisory Committee on Weather Control (H. T. Orville, Chairman), 1957: Final Report of the Advisory Committee on Weather Control. U.S. Govt. Printing Office, Washington, D.C. Vol. I, 32 pp., Vol. II, 422 pp.

Browning, K. A., and G. A. Monk, 1982: A simple model for the synoptic analysis of cold fronts. *Quart. J. Roy. Meteor. Soc.*, **101**, 893–900.

Bureau of Reclamation, 1983: *The Design of SCPP-1, 2d rev.*, Bureau of Reclamation, Denver, Colo., 61 pp.

Elliott, R. D., and W. A. Lang, 1967: Weather modification in the southern Sierra. *J. Irrig. Drain. Div., Am. Soc. Civ. Eng.*, 5644, **IR4**, 45–49.

Flueck, J. A., 1982: Comparative experimentation: some principles and prescriptions. *Teaching of Statistics and Statistical Consulting*, J. Rustagi and D. Wolfe, Eds., Academic Press, Inc., New York, 443–463.

Heggli, M. F. and D. W. Reynolds, 1985: Radiometric observations of supercooled liquid water within a split front over the Sierra Nevada. *J. Climate Appl. Meteor.*, **24**, 1258–1261.

——, L. Vardiman, R. E. Stewart, and A. W. Huggins, 1983: Supercooled liquid water and ice crystal distributions within Sierra Nevada winter storms. *J. Climate Appl. Meteor.*, **22**, 1875–1886.

Henderson, T. J., 1966: A ten year non-randomized cloud seeding program on the Kings River in California. *J. Appl. Meteor.*, **5**, 697–702.

Hobbs, P. V., 1975: The nature of winter clouds and precipitation in the Cascade Mountains and their modifications by artificial seeding. Part 1: Natural Conditions. *J. Appl. Meteor.*, **14**, 783–804.

——, 1978: Organization and structure of clouds and precipitation on the mesoscale and microscale in cyclonic storms. *Rev. Geophys. Space Phys.*, **16**, 741–755.

Hogg, D. C., F. O. Guiraud, J. B. Snider, M. T. Decker, and E. R. Westwater, 1983: A steerable dual-channel microwave radiometer for measurement of water vapor and liquid in the troposphere. *J. Appl. Meteor.*, **22**, 789–806.

Huggins, A. W., and A. R. Rodi, 1985: Physical response of convective clouds over the Sierra Nevada to seeding with dry ice. *J. Climate Appl. Meteor.*, **24**, 1082–1098.

Humphries, J. H., 1985: Applications of an airborne optical array probe for ground-based microphysical observations. *J. Atmos. Ocean. Tech.*, **2**, 253–259.

Ludlam, F. H., 1955: Artificial snowfall from mountain clouds. *Tellus*, **7**, 277–290.

Mielke, P. W., L. O. Grant, and C. F. Chappell, 1970: Elevation and spatial variation effect of seeding wintertime orographic clouds. *J. Appl. Meteor.*, **9**, 476–488.

Mooney, M. L., and G. W. Lunn, 1969: The area of maximum effect resulting from the Lake Almanor randomized cloud seeding experiment. *J. Appl. Meteor.*, **8**, 68–74.

National Academy of Sciences, 1973: Weather and climate modification: problems and progress. Report of Panel on Weather and Climate Modification. Washington, D.C., 258 pp.

Parish, T. R., 1982: Barrier winds along the Sierra Nevada mountains. *J. Appl. Meteor.*, **12**, 925–930.

Rangno, A. L., P. V. Hobbs, and L. F. Radke, 1977: Tracer and diffusion and cloud microphysical studies in the American River Basin. Final Report to the Bureau of Reclamation under Contract 6-07-DR-21140. University of Washington, Dept. of Atmospheric Science, Seattle, WA 98195, 64 pp.

Rauber, R. M., and L. O. Grant, 1986: The characteristics and distributions of cloud water over the mountains of northern Colorado during wintertime storms. Part II.: Physical distribution and microphysical structure. *J. Climate Appl. Meteor.*, **25**, 489–504.

Reynolds, D. W., T. H. Vonder Haar, and L. O. Grant, 1978: Meteorological satellites in support of weather modification. *Bull. Amer. Meteor. Soc.*, **59**, 269–281.

Rodi, A. R., A. J. Heymsfield, and N. Prasad, 1985: Precipitation formation in dry-ice seeding plumes. *4th WMO Scientific Conference on Weather Modification*, Honolulu, Hawaii, August 12–14, 71–76.

Sand, W. R., W. A. Cooper, M. K. Politovich, and D. L. Veal, 1984: Icing conditions encountered by a research aircraft, *J. Climate Appl. Meteor.*, **23**, 1427–1440.

Snider, J. B., and D. Rottner, 1982: The use of microwave radiometry to determine a cloud seeding opportunity. *J. Appl. Meteor.*, **21**, 1286–1291.

Stewart, R. E., and J. D. Marwitz, 1982: Microphysical effects of seeding wintertime stratiform clouds near the Sierra Nevada mountains. *J. Appl. Meteor.*, **21**, 874–880. ●