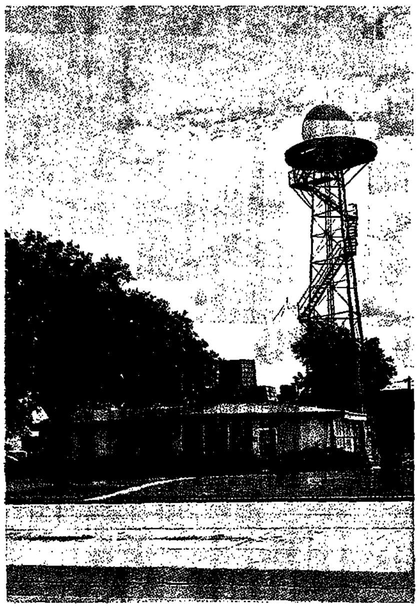
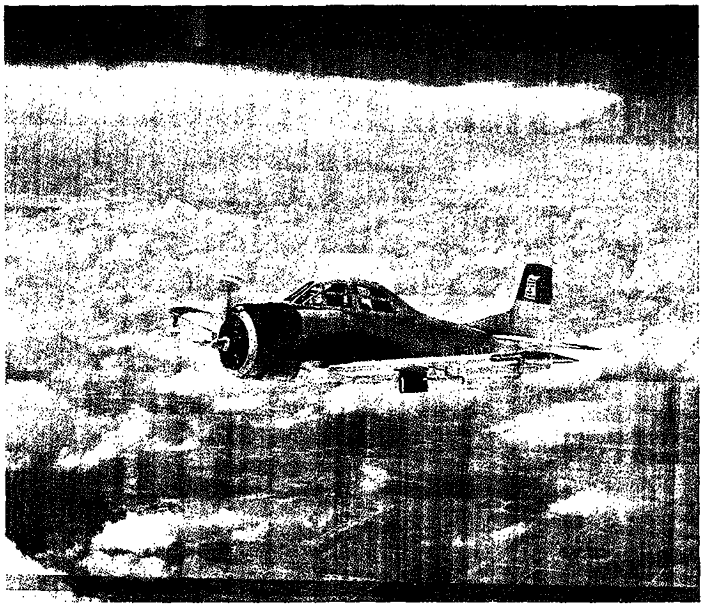
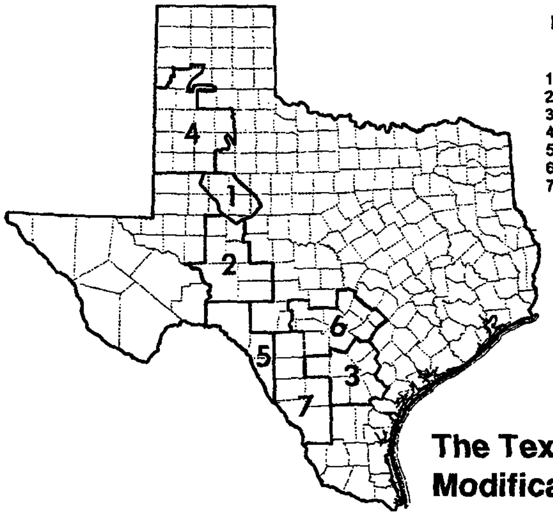
The Journal of Weather Modification







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The Texas Weather Modification Program

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Weather Modification Association

- THE JOURNAL OF WEATHER MODIFICATION -

COVER: *Upper left – Headquarters, with C-band radar and tower in background, of the West Texas Weather Modification Association, San Angelo, Texas. (Photo courtesy George Bomar)*

Upper right – The South Dakota School of Mines & Technology T-28 aircraft collected cloud physics data in 1994 as part of the Texas Weather Modification Project (it was supported by Texas Water Commission Grant No. 4200000082 and NSF Grant No. ATM 9104474). (Photo taken by William Woodley)

Bottom photo shows a map of the Texas Weather Modification Program (see Bomar et al., pg. 9)

EDITED BY:

James R. Miller, Editor
Connie K. Crandall, Editorial Assistant
Institute of Atmospheric Sciences
South Dakota School of Mines and Technology
501 E. St. Joseph Street
Rapid City, South Dakota 57701-3995 U.S.A.
Phone: (605) 394-2293
FAX: (605) 394-6061

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"REVIEWED"

THE TEXAS WEATHER MODIFICATION PROGRAM: OBJECTIVES, APPROACH AND PROGRESS

George W. Bomar
Texas Natural Resource
Conservation Commission
Austin, Texas 78711

William L. Woodley
Woodley Weather Consultants
Littleton, Colorado 80127

Dale L. Bates
San Angelo, Texas 76901

Abstract. Texas has a lengthy history of efforts by residents in semi-arid regions of the state to ameliorate the impact of periodic severe, even extreme, droughts by using cloud-seeding technology. Numerous rain-augmentation endeavors during the epic drought of the 1950s prompted the Texas Legislature to enact a statute governing the future use of weather-modification technology. That measure was followed by an effort, in concert with federal agencies, to assess the utility of rain-enhancement technology through a comprehensive, though often fitful, atmospheric-research program administered by Texas water agencies in the 1970s and 1980s. It was only after these multi-year research projects yielded substantial and compelling evidence that cloud seeding had efficacy with deep convective clouds in semi-arid portions of Texas that a coordinated, State-funded rain-enhancement program evolved, now covering nearly one-quarter of the state's acreage. With newer technologies being brought to bear in cloud-seeding operations and in the assessment of those activities, and with more political entities in the state now viewing cloud-seeding technology as a viable, long-term water management strategy and not a short-term, quick-fix to the drought problem, the foundation is being set for even more widespread usage of cloud seeding in the Lone Star State.

1. INTRODUCTION

The severe to extreme droughts so prevalent in Texas during the decade of the 1990s engendered among Texans a renewed appreciation for an adequate supply of fresh water. They also demonstrated just how vulnerable the state becomes when those supplies of fresh water dwindle to alarmingly low levels. With the state likely to double its population within the next 30 years, to as many as 35 million people, demands for adequate fresh water to meet the needs of so many water consumers are sure to soar, especially in times of deficit rainfall. Thus, with the dual threat of sustained population growth and inevitable drought, those planning for Texas' future are having to look for new, innovative ways to ensure that the supply of fresh water keeps up with the demand.

This growing need for adequate fresh-water supplies in arid and drought-stricken parts of Texas has focused renewed attention on alternative ways of conserving existing water resources and of procuring additional water by tapping into the abundant supply of moisture available in the Earth's atmosphere. Passage of the Texas Weather Modification Act by the Texas Legislature in 1967 was a tacit acknowledgment that the use of cloud-seeding technology had earned a measure of acceptance within the water-management community in Texas. At the same time, the law recognized many uncertainties remained with respect to the effectiveness of various forms of cloud seeding. Hence, the need to regulate the level of human intervention in cloud processes to protect the interests of the public, and to promote the development of a viable and demonstrable technology of cloud seeding, was addressed by that legislative act.

2. THE PROGRAM'S FOUNDATION: SOUND AND RELEVANT RESEARCH

To attain the objective mandated by the Texas Legislature to develop and refine cloud-seeding technologies, the State of Texas took a first step by linking up with the U. S. Bureau of Reclamation in 1973 to devise and demonstrate a viable cloud-seeding technology. Since then, an on-going, though often intermittent, research effort has ensued to corroborate and quantify the effects of timely seeding of convective clouds. Despite limited funding over the years, substantial progress has been made in pursuit of this goal. The evidence adduced from several years of intensive research has strongly suggested that researchers' efforts to explore, and appropriate, such a non-structural approach as weather modification for securing additional water supplies for a burgeoning population has been rewarded with more than a little success.

2.1 The HIPLEX Project

Texas' first step in scientifically investigating the value of cloud seeding technology for increasing water supplies was a cooperative effort with the U.S. Department of the Interior that was launched in 1973. The High Plains Cooperative Program (more popularly known as HIPLEX) was a part of "Project Skywater" that was designed to formulate an effective technology of rainfall enhancement to help supplement the Nation's fresh-water supply.

The Texas HIPLEX Program was designed as a long-term multi-phase research effort to develop a technology to augment West Texas summer rainfall. Due to Federal funding cutbacks, Texas HIPLEX was limited to its initial phase (1975 through 1980), which included the collection, processing and analysis of meteorological data in order to better understand the typical summertime cloud systems of west Texas. The data collected during the six summer field programs included surface and upper-air observations, and cloud physics, radar, satellite and rain gage data within an area of some 5000 sq. mi. in the southern High Plains of Texas (Fig. 1).

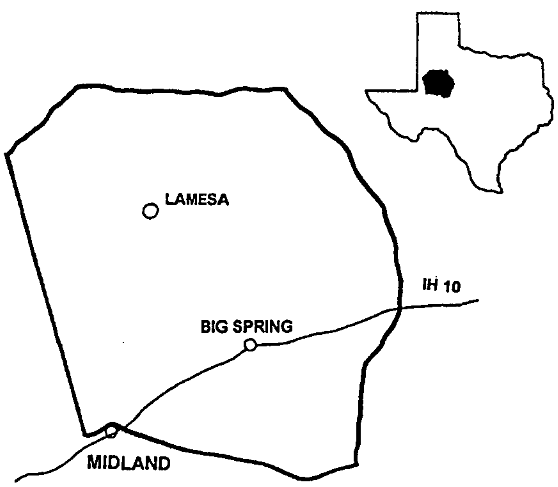


Fig. 1. Project area of the Texas HIPLEX Project, 1975-80.

Much of these data have been analyzed and insights into the physical processes responsible for convective rainfall in West Texas have been gained (see Riggio et al., 1983; and Matthews, 1983). These results indicate that most of the summer rainfall is produced by the larger, more efficient storms. More importantly, they indicate that a rain enhancement technology for West Texas ultimately must either address this type of storm or induce smaller, less efficient cloud systems to grow into their larger, more efficient counterparts. Jurica et al. (1983) were also led to the conclusion that multiple-cell convective systems offer more promise for significant rainfall enhancement than do isolated cumulus congestus.

2.2 The Southwest Cooperative Program

Randomized cloud seeding experimentation began in Texas in 1986 under the auspices of the Southwest Cooperative Program (SWCP) of Texas and Oklahoma. The SWCP was envisioned as a joint effort to develop a scientifically sound, environmentally sensitive, and socially acceptable, applied weather modification technology for increasing water supplies in the semi-arid southern High Plains. The primary initial focus was the testing of dynamic seeding concepts and procedures for the enhancement of rainfall (see Woodley et al, 1982). The sponsors of the Texas SWCP effort were the Texas Water Commission, the U.S. Bureau of Reclamation, the Colorado River Municipal Water District (Big Spring), and the City of San Angelo, Texas. Experimentation was conducted from a base in San Angelo, Texas during 1986, 1987, and 1989 and from a base in Big Spring, Texas in 1990 and 1994.

All experiments were carried out , within the same general area as that of the Texas HIPLEX Project (Fig. 1), in accordance with the SWCP Design Document (Jurica and Woodley, 1985) and SWCP Operations Plans (Jurica et al., 1987). In every case, the experimental unit was the small multiple-cell convective system within a circle having a radius of 25 km (areal coverage is 1,964 km^2) and centered at the location of the convective cell, which qualified the unit for treatment. The selection criteria are discussed extensively by Rosenfeld and Woodley (1989; 1993). The treatment decisions were randomized on a unit-by-unit basis and all suitable convective cells within the unit received the same treatment--silver iodide (AgI) in the case of a seed (S) decision or simulated AgI in the case of a no seed (NS) decision. Rainfall is estimated using radar for the "floating target" experimental unit, which floats or drifts with the wind.

During the randomized experimentation, suitable supercooled convective cloud towers within the convective cells received either simulated AgI treatment or actual AgI treatment near their tops (typical top heights of 5.5 to 6.5 km and top temperatures of -8°C to -12°C). The seeding devices were ejectable flares that produced 20 gm of AgI smoke during their 1.5 km free-fall through the upper portion of the cloud. Between 1 and 10 flares normally were ejected during a seeding pass, but more were ejected in a few instances in especially vigorous clouds. The flare ejection button was pressed approximately every second while the cloud liquid water reading was > 0.5 g/m³. In the simulated seeding passes no flares were actually ejected when the button was pressed, but the event was still recorded in the aircraft data system.

In the SWCP design, therefore, the treatment units are the convective cells, which contain cloud towers that meet the liquid water and updraft requirements. It is the cell that receives the treatment, and any effect of seeding should manifest itself first on this scale before it is seen in the experimental unit that contains the cells.

A total of 38 experimental units (18 Seed and 20 No-Seed) have been obtained in west Texas since experimentation began. In addition, 213 convective cells (99 Seed and 114 No-Seed) have been subjected to an analysis (Woodley and Rosenfeld, 1996), which suggests the S cells produced 2.63 times more radar-estimated rainfall than the NS cells by virtue of covering more area and having greater duration and larger rain volume rates. The results for rain volume, area, duration and merger are significant at the 5% level. The apparent rain increases took place without an appreciable increase in the mean echo heights of the cells, although the disparity might have been greater for the visible cloud tops had it been possible to measure them.

The rainfall results for the 38 experimental units (18 seed and 20 no seed) obtained in the Texas experimentation to date are provided by Woodley and Rosenfeld (1996). The ratio of mean seed to no seed rainfall is 1.45 by the end of the 150-min analysis period. This result is not statistically significant. This randomized experimentation was then terminated due to a lack of funding.

2.3 The TEXARC Project

With the entry of the State of Texas into the NOAA Federal/State Cooperative Program in Atmospheric Modification Research, however, an additional (but temporary) source of funding materialized. This was earmarked for physical studies of relevance to the randomized seeding experiment. As a consequence, the State of Texas took its first steps in 1994 and 1995 in implementing a research program involving the use an instrumented cloud-physics aircraft to investigate the physical processes that are operative within vigorous supercooled convective towers before, during, and following treatment with silver iodide. The multi-year research effort was known as the **T**exas **Ex**periment in **A**ugmenting **R**ainfall through **C**loud-Seeding (**TEXARC**) Project. Research activities were focused on an area of west central Texas near and west of San Angelo (Fig. 2). It was found that cloud microphysical structure is strongly dependent on the cloud-base temperature (CBT). When the cloud base is high and the CBT cool, very few raindrops are found at temperatures ranging between -5°C and -10°C and glaciation proceeds rather slowly in these "continental" clouds. When the cloud base is low and the CBT is warm, however, the west Texas clouds are more tropical in character, having raindrops at temperatures of -5°C to -10°C. Glaciation proceeds more rapidly in these untreated clouds (Rosenfeld and Woodley, 1997).

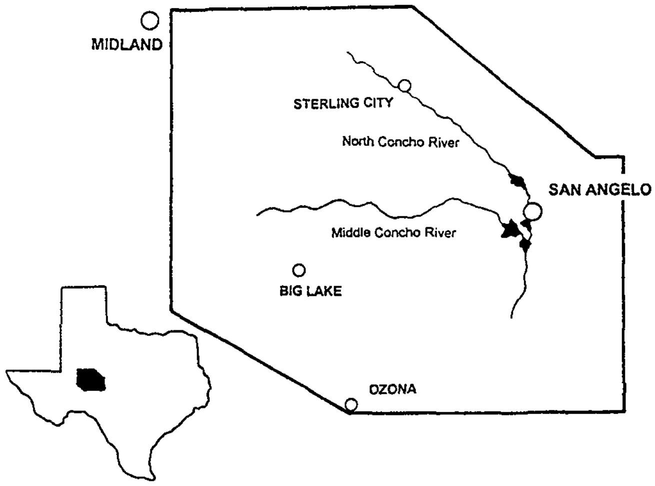


Fig. 2. Target area for the TEXARC Project, 1995-98.

It was found also that on-top seeding of supercooled cloud towers in "continental" clouds hardened them briefly in appearance but did not produce appreciable growth. As glaciation proceeded, the reflectivity of the cloud increased relative to the clouds in its environment and then it usually died. On the other hand, on-top seeding of clouds with warm cloud bases (i.e., CBT ≥ 18°C) appeared to result in rapid glaciation and vigorous cloud growth. This is consistent in what has been observed elsewhere in such clouds.

In clouds without supercooled rain it was observed that graupel grows too slowly to convert cloud water into precipitation-size particles (several mm) during the lifetime of the updraft except for the most vigorous and vertically developed clouds. This slow glaciation also does not produce a significant dynamic response in the clouds, rather the cloud normally glaciates during its collapse, accelerating its dissipation and leaving holes in the cloud field.

In clouds with supercooled rain, seeding leads to rapid freezing of the supercooled rain and its continued growth as graupel. This graupel appears to grow faster than supercooled raindrops under the same condition in accordance with theoretical calculations (Sednev, et al., 1996). The seeding also increases cloud buoyancy and further invigorates the updraft, while the cloud is still in a position to use it to support the growth of large precipitation particles.

These results emphasize the importance of when and where the various microphysical processes take place within the cloud and when and where the seeding takes place that is intended to alter these processes. Both the Rosenfeld/Woodley (see Rosenfeld and Woodley, 1993) conceptual model and these new results suggest it is crucial to produce glaciation artificially within the vigorous supercooled updraft region of the cloud when seeding for rain enhancement. It is in this region large artificially-nucleated precipitation-sized particles can be grown most efficiently. Accomplishing this through seeding requires great care in the placement of the nucleant either in the updraft directly near cloud top or in the strong inflow region at cloud base in well-developed convective systems.

3. OPERATIONAL WEATHER MODIFICATION IN TEXAS

3.1 Projects Begun Prior to 1985

Much of the rather meager amount of cloud-seeding for rainfall enhancement prior to 1985 was concentrated in a 3600-square-mile area of semi-arid West Texas, where the Colorado River Municipal Water District began seeding deep convective towers in 1971(Fig. 3). By virtue of sustaining a perennial, warm-season seeding program in the vicinity of Big Spring,

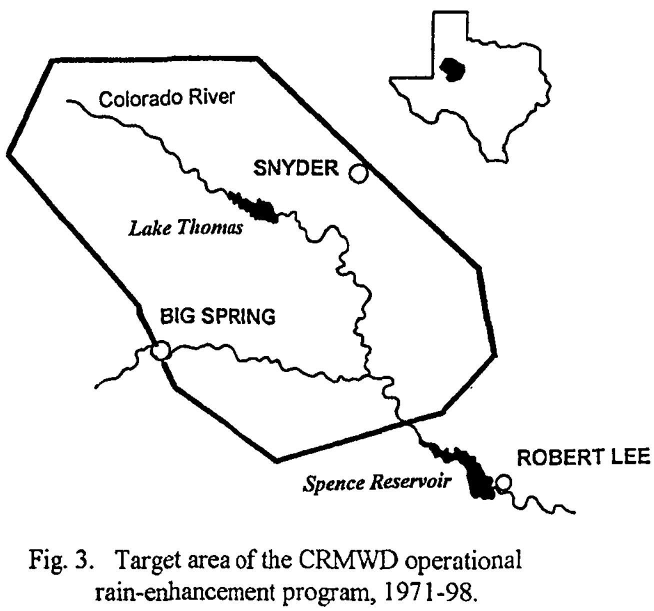


Fig. 3. Target area of the CRMWD operational rain-enhancement program, 1971-98.

Texas, the CRMWD's weather-modification effort became one of the most enduring rain-augmentation programs in the U.S. Others carefully observed the work of the CRMWD, including the City of San Angelo, which conducted its own 5-year rain-enhancement program in the latter half of the 1980s.

3.1.1 The CRMWD Program, 1971 to Present. The CRMWD rain-enhancement program has, since its inception in 1971, had as its primary objectives the augmentation of rainwater, and hence runoff, into two reservoirs owned and operated by the District on the upper Colorado River of Texas (Fig. 3). A secondary objective of the long-running program was to increase rainfall for the agricultural interests that predominate in the gently-rolling plains of West Texas. The dispersal of seeding material (silver iodide) was achieved at or just below cloud base using a twin-engine aircraft equipped with both wing-mounted flares and, at times, acetone generators.

In assessing the apparent effect of seeding of the CRMWD program, Jones (1988 and 1997) made use of the historical rainfall record (1936-1970) to calculate percent of normal rainfall at target and control stations. He also used these data to develop target-control regressions, which were used to predict rainfall in the seeded period (1971-1988, 1990-91, 1994-95 and 1997). The predicted and observed target rainfalls were then compared. The percent-of-normal analysis indicates 34 percent above-normal rainfall in the target area, while rainfall only increased 13 percent for the unseeded areas outside the target area during the seeded years.

A second analysis by Jones (1988) of the yields of unirrigated cotton in and around the target since seeding began in 1971 indicates increases of cotton production of 48 percent in the target, and 45 percent downwind of the target, while the increase in cotton yields for the same time frame in the counties upwind of the target was only 8 percent. If one assumes that rainfall has been the major control of cotton production over the entire West Texas region (an assumption generally regarded as fair), this result may be interpreted as further evidence for seeding-induced rain increases.

3.1.2 The San Angelo Program, 1985-89. The harsh drought of 1982-84 forced the City of San Angelo to examine the potential of cloud-seeding technology for mitigating the deleterious effects of drought over the city's watershed. A cloud-seeding program was launched in the summer of 1985, using aircraft with the capability of seeding convective towers from above cloud top as well as at or below cloud base. The same seeding methodology, using either wing-mounted or droppable pyrotechnics of silver iodide, was employed for five consecutive summers in a 6-million acre area around and west of San Angelo.

A regression analysis of observed rainfall within the target area suggested an overall effect of seeding of about 17 percent for the target for the 5-year program (Woodley and Solak, 1990). The area closest to the storage reservoirs had an apparent overall effect ranging between 27 and 42 percent. It was within this region that more than half of all seeding material was dispersed.

3.2 Projects Launched Since 1985

With concern growing over the availability of ground water to meet the increased demand for fresh water, other cloud-seeding projects materialized during the 1980s. One project focused on treating deep convection over the drainage basin of the Edwards Aquifer, a vast underground 'reservoir' that furnishes much of the Texas Hill Country, including the metropolis of San Antonio, with its fresh water. The City of Corpus Christi conducted a short-lived cloud-seeding program to put more runoff into a reservoir (Choke Canyon) that serves that coastal city. However, these programs did not thrive for long, principally because of the concern for flash flooding in what is one of the three most flash flood-prone areas of the U.S. Constraints were imposed on the projects to the extent that many seeding opportunities had to be given up due to the threat of heavy rains in densely-populated areas.

4. BACKGROUND FOR THE CURRENT STATEWIDE PROGRAM

From the time prior to World War I, when C. W. Post attempted to 'shake' rainwater out of towering cumuli along and just below the Caprock region of West Texas (1911-1914), various weather-modification methodologies have been used in the Lone Star State to prompt warm-season cumulus clouds to live longer and shed much-needed rainfall. Rain-enhancement projects sprung up intermittently in parts of semi-arid West Texas in the decades between the two world wars and during the epic drought of the 1950s, usually as a measure of last resort to ameliorate the impact of a prolonged dry spell. Even after legislation was adopted in 1967 to regulate the use of cloud-seeding technology within the state, rain-enhancement programs adopted by various water interests were for the most part locally-controlled and funded, with minimal interface from the State.

The lack of state involvement in the more than a dozen independently-financed and managed weather modification projects prior to 1970 meant that the bulk of these efforts received a minimum of rigorous analysis. In fact, most of the projects were poorly documented, if at all. The impact of cloud-seeding was seldom quantified, and perceptions of the efficacy of the efforts were for the most part a function of who happened to be asked. By today's standards, methods of cloud seeding were rather primitive. For instance, many of the projects conducted between World War II and the passage of the Texas Weather Modification Act (in 1967) involved WWII-vintage aircraft and dry ice.

4.1 Role of Water Conservation Districts

What would eventually serve as a foundation for funding, designing, and implementing cloud-seeding operations on a large-scale basis in Texas began to evolve during the historic 1950s drought. Independent *water districts* began sprouting in rain-short areas of West and Southwest Texas after a precedent was established in the mid-1950s by the High Plains Underground Water Conservation District. This district, encompassing all or parts of 15 counties in northwestern Texas and covering some 6.9 million acres above the Caprock (Fig. 4), materialized in order to monitor, and eventually govern, the use of fresh water from the vast Ogallala Aquifer that underlies vast portions of the U. S. Great Plains, from Nebraska to near the Permian Basin in far West Texas. Given *ad valorem* taxing authority, the District was furnished

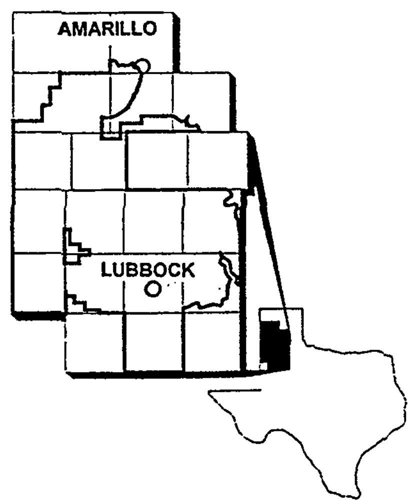


Fig. 4. Target area for the rain-enhancement program of the HPUWCD, 1997-98.

the financial wherewithal to set up a staff to quantify its ground-water resources and regulate the use of that ground water to ensure that water supplies from the aquifer would be adequate to meet the fresh-water needs of a growing populace.

Subsequent state legislation encouraged the formation of other, similarly-constructed water districts in semi-arid parts of Texas, though the 42 districts formed after 1985 (and encompassing all, or parts, of 80 Texas counties) were considerably less expansive than the original High Plains district based in Lubbock. In every instance, however, the fundamental motivation for establishing these districts (many of which are single-county districts) was to have a legal mechanism in place to control the draw-down from, and abet the recharge to, the aquifers that underlay the districts. Perhaps serendipitously, the arrangement of these districts afforded the locals a fiscal mechanism by which programs like cloud seeding for rainwater-augmentation could be equitably paid for within their respective areas of jurisdiction.

The first water district to use some of its funds to apply an innovative water-development strategy, such as precipitation enhancement through cloud seeding, was the Colorado River Municipal Water District, based in Big Spring. One of Texas' preeminent pioneers in developing new and innovative water-management strategies, Owen H. Ivie, as general manager of the CRMWD, was preeminently responsible for the program launched in 1971. After using a contractor for cloud-seeding services in the early years of his program, he saw the merits of committing the District to a long-term rain-enhancement program by securing its own aircraft, weather radar, and qualified staff to run its cloud-seeding operation during the growing season.

4.2. Origins of a Statewide Program

Despite the apparent successes of the two multi-year projects based in Big Spring and San Angelo, it was not until 1995 that interest in using cloud-seeding technology grew enough to foster serious consideration of implementing a far-reaching, region wide cloud-seeding effort. The impetus for a statewide weather-modification program was born in the region west of San Angelo, where cloud seeding had been conducted extensively in the latter half of the 1980s. During that 5-year program, numerous ranchers living west of the city in several counties whose rivers and streams supplied water to the City's reservoir system had observed what they considered to be a positive response in many of the towering cumuli seeded by the City's contractor. These counties already had in place single-county water districts, which afforded a convenient mechanism for raising funds to support the reinstatement of a regionwide cloud-seeding program.

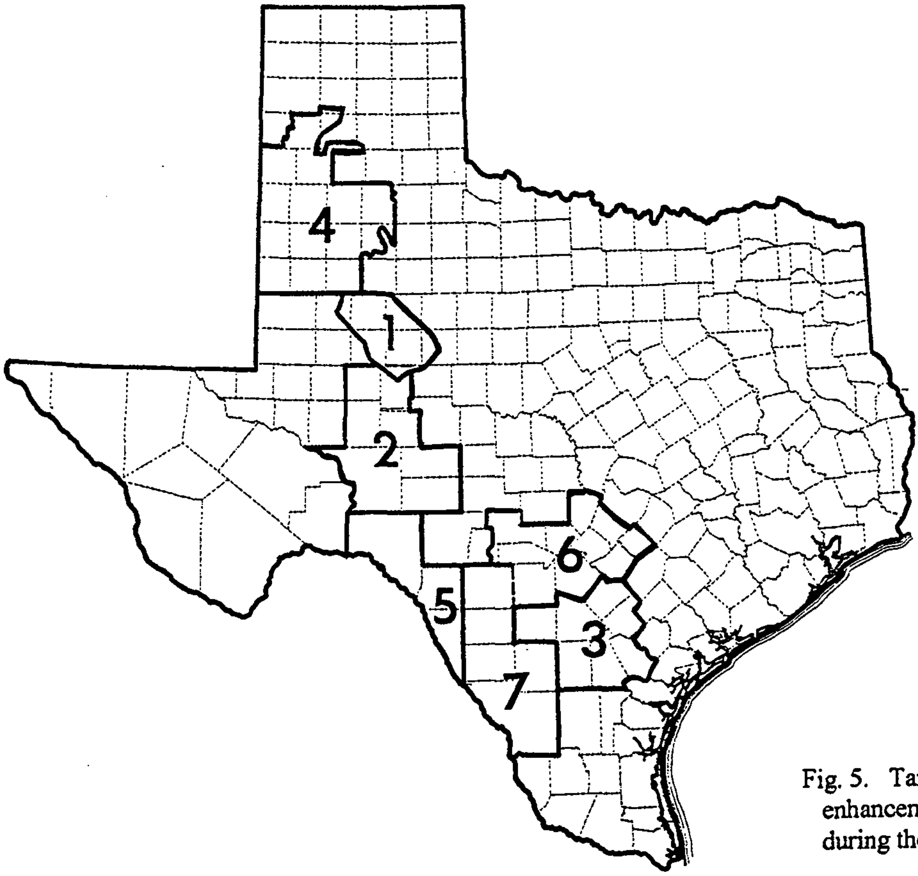
Water-district officials from these counties began holding public meetings in and near their respective county seats and invited staff from the State's water agency to attend and give formal presentations on the state of weather-modification technology for rainfall-augmentation. Soon, these counties had formed a weather-modification alliance, called the West Texas Weather Modification Association, to raise funds and implement cloud-seeding operations. The alliance was formed under the authority given the water districts to quantify and protect ground-water reserves in the aquifers beneath them. Cloud seeding was viewed by these officials as a cost-effective means of recharging the aquifers and lessening the rate of withdrawal from the aquifers.

Landowners and water-district officials in Irion and Crockett Counties of West Texas learned more about the potential of cloud seeding for augmenting rainfall in the summer of 1995, at which time the State's water agency was conducting a series of cloud-seeding experiments in the Big Spring, Texas area, known as the TEXARC Project.

As a severe drought ravaged much of West Texas in 1995, other nearby counties joined with Irion and Crockett Counties to form the West Texas Weather Modification Association (WTWMA). The establishment of this alliance of eight counties to promote the use of cloud-seeding technology would serve as a prototype for other rain-enhancement projects that would form elsewhere in West, and in South, Texas in the years to follow (Fig. 5, project number 2). With a "target" area of 7.2 million acres, a contractor was identified and both cloud-base and cloud-top seeding activities got underway in May 1996.

4.3. Local Supervision of Seeding Operations

An executive Board consisting of representation from the eight participating counties was established to facilitate decision making as the project ensued. Despite the fact that some counties making up the WTWMA target area were considerably larger than others, each county was assigned one vote. Moreover, each voting delegate had to be an elected official (e.g. water district Board member, county commissioner, city official). Such a policy ensured that control of the program resided, and was maintained, at the "grass-roots" level. Furthermore, the program was paid out of revenue raised through *ad valorem* taxes by each county. A county share's was



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(millions of acres)

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	Total	35.89

Fig. 5. Target areas of the seven rain-enhancement projects to be in operation during the summer of 1999.

determined by the total amount of acreage in that county. In one or two instances, where counties without water districts were participants, the share of funding from that county was provided by a county commissioners' court or through revenue supplied by a landowners' association.

The first year of cloud-seeding was paid solely by monies raised by the water districts constituting the WTWMA. The way these member counties linked themselves together to plan and pay for the rain-enhancement project garnered the attention of both regional and national news media. The fact that the region was in the throes of a worsening and spreading drought undoubtedly contributed to the fascination sown by both media groups and by political interests statewide. In the early weeks (June 1996) of the newly-formed cloud-seeding operation based in San Angelo, reporters from several major television news organizations (ABC, CNN, and NBC) visited the project site to interview project organizers and personnel. Several major newspapers did feature articles on the project as well.

Perhaps the most appealing aspect of the way the West Texas group organized themselves consisted of the control afforded the program at the local level. The executive Board made all decisions relative to the conduct of the program. Representation from each participating county meant the diverse needs of each major enterprise could be accommodated. For instance, a county with a heavy investment in cotton production would prefer to have a minimum of rainfall during the time of harvest in the autumn; input from that county through its representative on the Board would ensure that the county (or some large sector of that county) would be excluded from any advertent weather-modification activity during the period specified.

The West Texas group had as its preeminent objective to help as many as possible residing within their target area and not to hurt anyone. (In fact, the State water agency regulating the use of cloud seeding for rain enhancement is required to ascertain, to the extent technologically possible, that the proposed weather-modification program will not "dissipate the clouds nor prevent their natural course of developing rainfall in the area to the material detriment of people or property" within that area; such a finding must be made before the Texas Natural Resource Conservation Commission (TNRCC) can, and will, issue a permit for the project.)

Moreover, the WTWMA maintained a rain-gage network to assess soil-moisture conditions during the course of the cloud-seeding operation. These rainfall data were used to prioritize those areas within the target region most, and least, in need of rainfall. In many instances, it was possible to specify an area as small as a fraction of a county where rainwater was, or was not, needed. This policy afforded the participating counties and ranchers within them an added sense of control of the program.

4.4. The Proliferation of Projects

Using the WTWMA organizational model, a second rain-enhancement program was formed in South Central Texas, south of San Antonio and some 250 miles removed from the WTWMA site. A water district (known as the Evergreen Underground Water Conservation District) based in Jourdanton, Texas served as the nucleus for this 7-county, 4.4 million-acre project (Fig. 5, project number 3). The alliance of counties, called the South Texas Weather Modification Association (STWMA), established a governing Board, developed specifications for a warm-season rain-augmentation program, went out for bid, then secured a contracting firm to perform the actual seeding operations.

A third rain-enhancement project, covering some 6.87 million acres in the Texas High Plains, materialized in 1997. This project, based in Lubbock, was unlike its two predecessors in that it was sponsored by a lone and very large underground water-conservation district covering all or parts of 15 counties in the High Plains of Texas. That district, the HPUWCD, already had in place a governing board as well as a network of county committeemen. Those two mechanisms were used to provide the kinds of locally based input needed to structure, then supervise, the cloud-seeding program to the needs of constituents.

Still more projects, encompassing an additional 12 million acres in southwest and south Texas, were drawn up for implementation in 1998. One of them got underway just weeks before the residue from a tropical storm (Charlie) dumped flash floods in Val Verde County, the heart of the Texas Border Weather Modification Association (TBWMA) target area (Fig. 5, project number 5). (Cloud-seeding operations had been suspended a full 20 hours before the onset of those torrential, flood-producing rains inundated much of the city of Del Rio in August 1998.) The project, governed similarly by a multi-county Board, resumed cloud seeding soon after the flood water receded.

4.5. State Support of Weather Modification

A pivotal development in the statewide weather-modification program can be traced to action by the 75th Texas Legislature, which in 1997, appropriated for the first time ever a substantial amount of funds to help the various cloud-seeding projects pay for their operations. The State support was given to those water districts sponsoring cloud seeding on a 50-50 cost share basis. The amount of State funding to each project was determined strictly on a per acreage basis. This arrangement meant that, for every $0.0425 per acre raised at the local level, an equivalent amount was contributed by the State water agency (TNRCC). Funds totaling $4.197 million were also made available for operations during the warm seasons of 1998 and 1999.

To unify the various rain-enhancement projects within Texas, an 'umbrella' organization was formed in 1997 known as the Texas Weather Modification Association. A voting representative from each of the state's five operational cloud-seeding programs served on the Association's executive Board. The TWMA worked to resolve problems encountered with the use of various types of flares at the five project sites. Moreover, the association advises the TNRCC staff in the allotment of state revenue to help pay for the weather-modification programs. The group also sponsored training sessions for project personnel, including specialized training from a scientific consultant for those meteorologists running the programs.

The end result of the collaborative efforts of state and local officials to orchestrate a well-designed, coordinated weather-modification effort for the state of Texas has fostered a virtually ideal environment for continued research and development of an appropriate cloud-seeding technology for the region. This was evidenced by the successful completion of the 1998 TEXARC Project in the vicinity of San Angelo, Texas. It is also apparent in continued monetary support from the State water agency, with the bright prospect that State funding will be maintained through at least the summer of 2001 for both operational cloud seeding activities and relevant research and assessment work in support of those activities.

5. RECENT TEXAS RESEARCH FINDINGS OF RELEVANCE TO ITS OPERATIONAL PROGRAMS

The conduct of the TEXARC Project, initiated in 1994 and continued until the present day, has furnished a number of new insights on how best to carry out seeding operations, including the recognition of which convective clouds are more "seedable" as well as the optimum seeding strategies given an array of atmospheric conditions.

5.1 The L Coalescence Parameter and First-Echo Heights

Perennial questions in all rain enhancement programs are whether, when, where and how cloud seeding is to be conducted. A question being faced currently in some of the Texas programs that have decided to employ hygroscopic for rain enhancement in addition to conventional AgI methods is when either AgI or hygroscopic seeding is to be employed. Some might argue this use of hygroscopic seeding for rain enhancement in the manner of Mather et al. (1997) is premature. Others might argue the state of knowledge with respect to hygroscopic seeding is no worse than that for AgI seeding and there is no reason not to employ hygroscopic seeding in an operational context.

Because hygroscopic seeding is being employed at some places in Texas, it is appropriate to develop some guidelines for its use and evaluation. If the cloud tops are warm (i.e., > 0°C), hygroscopic seeding is the only option, if indeed any method is to be employed. If the tops are supercooled and loaded with raindrops, hygroscopic seeding is not the better choice. It makes no sense to seed to enhance coalescence and the formation of raindrops if natural conditions are already producing them in large concentrations. Further, model simulations of hygroscopic seeding show no effect from the seeding of highly maritime clouds containing raindrops. It is important, therefore, to predict when the clouds will produce raindrops naturally and to determine in real time whether the clouds are producing raindrops naturally.

One way of predicting in advance whether the supercooled (T about –10°C)) portions of clouds on a particular day will contain raindrops is to calculate the Mather L coalescence discriminator defined as

$$L = 8.6 - CCL + 1.72(PB)$$

where CCL is the temperature at the convective condensation level and PB is the potential buoyancy, defined as the temperature difference between the temperature of an air parcel rising from the CCL to 500 mb and the 500 mb temperature itself (Mather, 1986). The warmer the CCL and the smaller the PB the more likely the supercooled portions of the clouds will contain raindrops. Thus, the probability of raindrops increases as L decreases and vice versa. This was found to be the case in South Africa where the L parameter was derived.

The L parameter also performs well in Thailand as a predictor of in-cloud coalescence as shown in Figure 6. Figure 6 is a scatter-plot from Sukarnjanaset et al. (1998) in which each plotted point represents L vs. either the median maximum or the mean maximum droplet or frozen droplet size in the supercooled portions (about –8°C) in Thai clouds. The correlations for the mean and median relationships are – 0.65 and –0.66, respectively. Best fits to the mean (solid line) and median (dashed line) data are shown. The results indicate that the droplet sizes increase as L decreases.

The value of the L parameter is being investigated in Texas by relating the L parameter to first-echo heights, because first-echoes should be indicative of the presence of raindrops. So far, the L parameter has

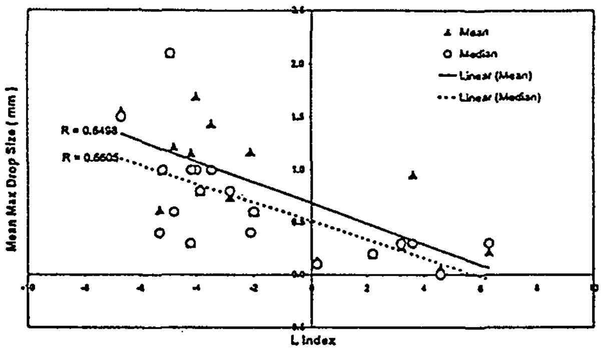

Fig. 6. Daily mean and median maximum droplet sizes in the range of -8C to -12C versus the Mather coalescence parameter (L)

been calculated for 29 days during the 1998 season using both the San Angelo and Del Rio soundings. The first-echo top heights for the same days have been calculated using TITAN software and the San Angelo WTWMA WSR-74 5-cm radar. A scatter plot between L (the abscissa) and the first echo heights (ordinate) have been constructed for Midland and Del Rio soundings as shown in Figures 7 and 8, respectively, along with the linear correlation coefficients and best fit lines.

Note there is a strong positive correlation between L and the first echo heights. This means as L decreases the first echo heights decrease. For large negative L values the top heights of the first echoes are < 5 km in most instances, meaning the echoing portion of the cloud containing the raindrops is warmer than 0°C. It is questionable hygroscopic seeding would enhance the rainfall from such clouds.

Because the rain in the clouds increases as L decreases, it should be possible to use the L parameter to determine which type of seeding should be employed. When L is large and negative (e.g., L < -2) silver iodide seeding should be employed instead of hygroscopic seeding if seeding is to be done. As L increases (e.g., L > 5), however, it becomes less likely the clouds will contain raindrops and hygroscopic seeding should take precedence over silver iodide seeding. Regardless of which method is chosen at the outset, the decision should be checked using the first echo heights. Whenever the first echo heights are low, hygroscopic seeding is not the

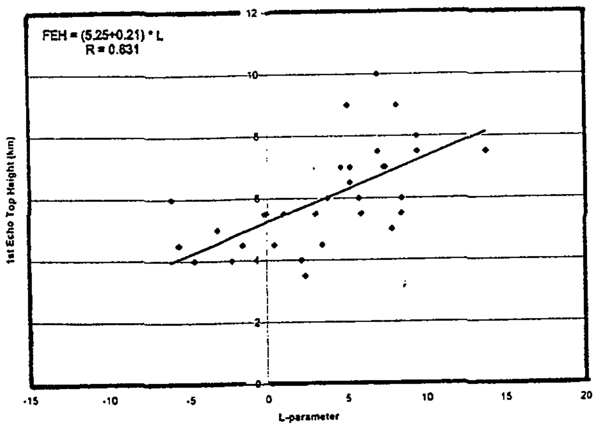

Fig. 7. Values of L-parameter versus first-echo heights using Midland sounding data, for all 1998 operational days.

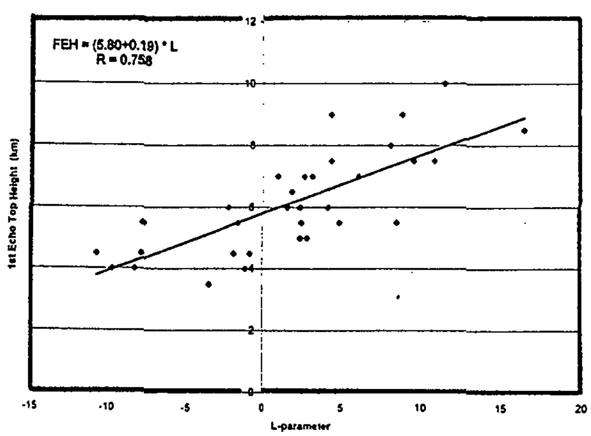

Fig. 8. Values of L-parameter versus first-echo heights using Del Rio sounding data, for all 1998 operational days.

better choice regardless of the L parameter. Silver iodide should be used in those circumstances.

5.2 Evaluation of Operational Seeding Activities

The Texas program has adopted the view that no operational seeding should be conducted without some provision for its evaluation. This agrees with at least one of the points made by Kessler (1998) in his critique of current operational seeding programs in Texas and Oklahoma. Evaluation can take the form of target-control historical regressions. It can also take the form of physical evaluations even though they may not address directly whether the seeding has produced more rain on the ground. Examples of both types of evaluation are provided here.

5.3 First-Echo Heights and Hygroscopic Seeding

A physical means of evaluating hygroscopic seeding is embodied in Figures 7 and 8 in which first-echo heights are plotted vs. L. If operational seeding is conducted on days when L is large and positive, the first-echo heights will be high and supercooled. By identifying a seeding area of effect on such days, one might look at the tops of the first echo heights in the presumed area of effect to determine whether they have been lowered in this area as a result of seeding. If no lowering is evident over the course of a number of seeding events, one would have reason to question the effectiveness of the hygroscopic seeding. On the other hand, if hygroscopic seeding is effective, the mean first-echo heights as a function of L should be less than for clouds that did not ingest the hygroscopic material. This analysis will be pursued in the Texas evaluation effort.

5.4 Satellite Inference of Cloud Microstructure for Evaluation of Cold-Cloud Seeding

The new method of Rosenfeld and Lensky (1998) to infer cloud microstructure using AVHRR satellite imagery shows great promise for the physical evaluation of seeding experiments. The AVHRR on NOAA-14 measures the radiance at five wavebands of 0.65, 0.9, 3.7, 10.8 and 12.0 microns with a sub-satellite resolution of 1.1 km. The visible wave band (0.65 microns) is used to select points with visibly bright clouds for the analyses. The thermal infrared (0.9 microns) is used to obtain cloud-top temperatures. Cloud-top particle size is inferred from the solar radiation component of the 3.7-micron wave band. Retrieval of particle size at cloud top is based on the fact that water absorbs part of the solar radiation at the 3.7-micron wave band. Although the back-scattered solar radiation is determined mainly by the surface area of the particles, the amount of absorption is determined by the volume of the particles. Therefore, larger particles absorb more and reflect less, so that clouds that are made of larger droplets are seen darker in the reflected 3.7-micron radiation. Knowing the energy radiated from the sun and the portion of that energy reflected back to the satellite sensor, the fraction of the solar energy absorbed can be retrieved. This provides the basis for calculating the ratio between the integral volume and integral surface area of cloud particles in the satellite measurement volume. Conventionally, this ratio has been defined as the particle effective radius, r.

5.4.1 Quantifying the Effective Radius of a Particle

The vertical evolution of reff from base to top of a growing convective cloud can be obtained by viewing the cloud in the satellite imagery during its vertical growth phase. However, the NOAA satellite is a polar orbiter, providing only a snapshot image of a specific portion of the earth only once or twice a day. Thus, a single cloud cannot be viewed continuously in the imagery provided by the polar orbiter. This difficulty is overcome by observing an area containing a convective cloud cluster composed of cloud elements at various stages of vertical growth. This allows the compositing of the reff calculations for many clouds as if they represented a singe cloud at different times, assuming the reff of a given cloud top is similar to the reff of a taller cloud when it grew through the same height.

Cloud-top temperature (T) is uniquely related to the depth of convective clouds above their bases in a given area on a given day by calculating T vs. height relationships from the nearby atmospheric sounding. In doing this, it is possible to use temperature as a measure for cloud vertical development.

Cloud top at a given T can have a range of reff values. For presentation of the dependence of r_{eff} on temperature (and therefore, height), the median and the 10th, 25th, 50th, 75th and 90th percentiles of the reff for each 1°C interval of cloud top temperature were calculated for the three areas shown in Figure 9. The image is for June 10, 1998, and the areas 1-3 are in West Texas. The number 3 in area 3 is near Big Spring, where base AgI seeding by the Colorado Municipal Water District was being conducted before, during, and after a pass of the NOAA-14 satellite. In addition, on-top seeding also had been conducted between Big Spring and San Angelo two hours earlier by the seeder aircraft of the West Texas cloud seeding program. The seeded clouds rained and then dissipated, producing a strong outflow that passed Big Spring moving to the northwest. The Big Spring convection seen in an E-W line to the north of Big Spring was initiated on this outflow boundary. Thus, it is conceivable the clouds in areas 1 and 3 ingested the silver iodide released by the two seeding programs, especially those in area 3 where seeding was taking place at the time of the image. Further analysis, using seeding track information, is needed to verify that such ingestion of seeding material did occur.

5.4.2 Depiction of Reflectance and Effective Radius

An important step in the understanding of the highly complex interactions among cloud structure, temperature, thickness, reff and the input aerosols is a clear visualization of these multi-parameter data. This is facilitated by coding various combinations of visible reflectance, T and reff as different colors, shown in Figure 9, according to the following scheme: a) The visible reflectance modulates the red (brighter is redder), b) the reflectance component at 3.7 microns, which is a surrogate for reff, modulates the green (smaller reff is greener), and c) the 10.8 microns brightness temperature modulates the blue (warmer is bluer) (For a more detailed explanation of this color scheme, the reader is urged to consult the paper by Rosenfeld and Lensky, 1998). Ice particles are typically much larger than cloud droplets at the same temperature, thus more absorbing at 3.7 microns. Therefore, ice clouds or snow on the ground appears as having very large reff, or very low green in the color images. For the same reason, small reff indicates water clouds, even at temperatures below 0°C, where the cloud is composed of supercooled water. Such clouds appear yellow in the color scheme.

The most obvious feature in Figure 9 is the large red mass on the center-right. It is the anvil top of a cumulonimbus to the N and NE of Big Spring. It is red because it is bright (high red), very cold (low blue) and has large particles (low green). The SW portion of the Cb is still active and magenta-colored clouds are noted on the periphery of this active area, to the SW in area 3 and in the center of area 1. There are no clouds with the same coloring in area 2.

Looking first at the r_{eff} plots for the three areas, the vertical colored lines on the left margin of the plots identify the growth zones within the clouds. The vertical yellow line gives the extent of the diffusional growth zone in which r_{eff} increases slowly with height. The vertical green line identifies the zone of coalescence growth in which r_{eff} increases more rapidly with height. The vertical

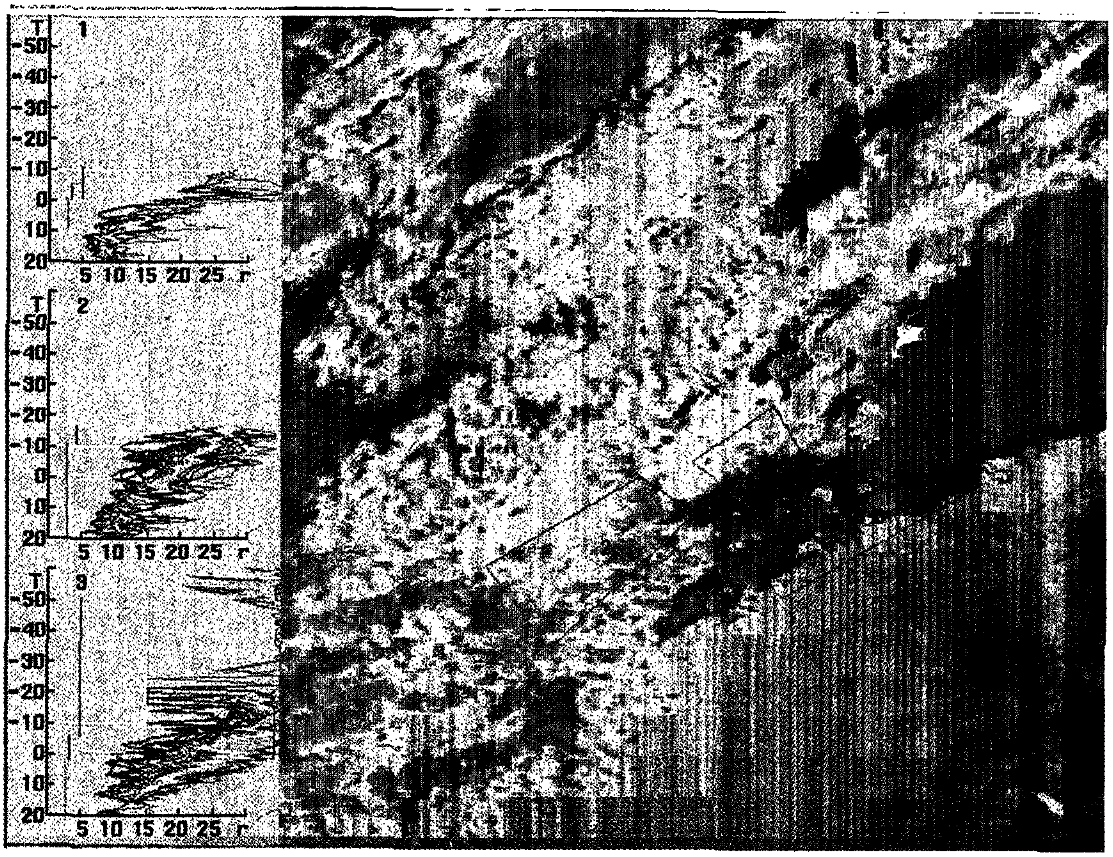

Fig. 9. A NOAA/AVHRR image from June 10, 1998, 20:54 GMT, of convective cloud development over West Central Texas, in the vicinity of Big Spring (approximate location designated by "3")

blue line, which is not shown in area 2 but exists in areas 1 and 3, is the fallout zone in which the larger drops fall out about as fast as they are replaced such that r_{eff} remains fairly constant with height. Finally, the vertical pink line identifies the zone of glaciation in which r_{eff} increases rapidly with height, reaching saturation at 30 microns where glaciation is complete. Also shown in the extreme left of the panels is a white line showing the number of pixels vs. height.

Focusing on area 2 and the median plot (the interface between the yellow and green lines), note the effective radius increases to cloud top where the temperature is about −15°C. Most of the cloud depth has coalescence growth of the cloud droplets (identified by the vertical green line). Because r_{eff} = 14 microns is usually indicative of precipitating cloud, many of the clouds in area 2 are likely precipitating, but they are not completely glaciated since r_{eff} does not reach 30 microns, which is usually indicative of complete glaciation (Gerber, 1996; Rosenfeld and Gutman, 1994). According to the plot only the cloud tops are partially glaciated.

In areas 1 and 3 the increase of the effective radius is more rapid with height. The zones of coalescence growth are shallower, there is a shallow fallout zone, and early complete glaciation is noted, achieved at temperatures between -5C and -10C. Such early glaciation may be suggestive of an effect of seeding, since the purpose of the seeding is to form ice earlier and at warmer temperatures in the cloud life cycle. This gives the seeding-induced ice particles more time to grow to precipitation size in the updraft regions.

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Simultaneous Operational AgI and Hygroscopic Flare Seeding in Texas: Rationale and Results

William L. Woodley
Woodley Weather Consultants
Littleton, Colorado

and

Daniel Rosenfeld
Hebrew University of Jerusalem
Jerusalem, Israel

Abstract A case study on 11 August 1996 involved simultaneous operational seeding of clouds to the W and SW of San Angelo, Texas, with hygroscopic flares at cloud base (T = 16°) and with ejectable AgI flares near cloud top (T = –8°C). Twenty-three hygroscopic flares were expended over 99 min while 95 AgI flares were expended over 96 min in the same area of clouds. The rationale for these dual seedings is discussed. This case was evaluated with San Angelo, Texas, NEXRAD radar data by calculating the lifetime properties of the seeded and non-seeded cells. This included the derivation of echo height vs. rainfall relationships. No cloud physics data were available. Although some of the seeded clouds produced heavy rainfall, there were a few unseeded clouds within range of the radar that produced comparable rainfall amounts. Thus, the data do not permit an unequivocal assessment of the effects of dual simultaneous hygroscopic and silver iodide seeding on this day.

1. INTRODUCTION

A case study on 11 August 1996 involved the simultaneous operational seeding of clouds to the W and SW of San Angelo with hygroscopic flares at cloud base (T = 16°C) and with ejectable AgI flares near cloud top (T = –8°C). This exploratory operational exercise in rain enhancement was predicated on the conceptual model guiding hygroscopic seeding experiments on deep clouds (Mather et al., 1997). According to the latest version of this model, hygroscopic flare seeding apparently increases rainfall by the following steps: 1) introduction of cloud condensation nuclei (CCN) at cloud base by burning hygroscopic flares, 2) preferential activation of the larger CCN from the flares, leading to a broadening of the cloud droplet distribution, 3) growth of the larger cloud droplets into raindrops by natural coalescence processes in clouds which could not otherwise have "grown" raindrops through warm-rain processes, 4) the transport of the raindrops into the supercooled portion of the cloud where the raindrops freeze due to their larger size, 5) invigoration of the cloud due to the released latent heat and growth of the frozen drops to large graupel by accretion of the cloud water resident in the updraft, and 6) increased radar-estimated rainfall at cloud base and presumably more rainfall at the ground, when the enhanced water mass moves downward through the cloud.

Steps 4 and 5 in the conceptual model call for the natural freezing of the raindrops induced by the hygroscopic seeding and their growth as graupel by accreting the cloud water. Studies in Thailand (Sudhikoses et al., 1998) suggest clouds containing supercooled raindrops will glaciate nearly twice as fast as clouds without raindrops (e.g., 6 min vs. 10 min for the supercooled cloud water content to drop to 50% of its initial maximum value). This supports the step in the hygroscopic seeding conceptual model calling for the freezing of the raindrops induced by the hygroscopic seeding. If the clouds are seeded further with silver iodide (AgI), the glaciation will be accelerated (Rosenfeld and Woodley, 1997; Sudhikoses et al., 1998) . Because early freezing of supercooled raindrops to promote the formation and growth of graupel is a goal of the seeding of deep clouds, AgI seeding was superimposed on clouds seeded with hygroscopic flares on 11 August 1996 with the expectation the dual seeding would produce a recognizable seeding signature in the radar data.

The coupled seeding on 11 August 1996 was viewed at the time as a one-time event unless the seeding signature was so strong as to be unequivocally caused by the seeding. It may be the first time such dual seeding has been done in either a research or operational context. What happened is recounted here.

2. RESULTS

Both seeder aircraft were airborne before 1530 CDT. Cloud base was at 2.1 km at a temperature of 16°C. The PPI presentation at 2007 GMT (1507 CDT, i.e., CDT = GMT – 5hrs) from the San Angelo NEXRAD radar is shown in Figure 1. The distance between range rings is 50 km and the angular width between the depicted azimuths is 30°) The area of interest for operational seeding was a short line of broken echoes SE-SW of San Angelo between 45 and 70 km. The first hygroscopic flare was ignited at 1549 CDT 55 km from the radar, ranging between azimuths of 209° and 235° during the first 20min of base seeding. The first AgI flare was ejected at 1558 CDT 67km to the SSW of San Angelo. By 1607 CDT both aircraft were seeding in the same area as shown. The echo presentations at 2054 GMT (1554 CDT) and 2117 GMT (1617 CDT) are given in Figures 2 and 3. The new echo development about 75km to the W of the radar had not been seeded at this time.

The echoes continued to develop to the NW as they dissipated at the SE end of the broken line. The base and top seedings moved NW with the new echoes (Figures 4 and 5). The echo mass had become better organized by 2210 GMT (1710 CDT) under continuing base and top seeding (Figure 6). The last radar image was at 2216 GMT (1716 CDT) (Figure 7) but seeding continued at cloud base until 1728 CDT and at cloud top until 1734 CDT. The reason for the lapse in radar data is unknown. The echo mass continued strong in the area of seeding through at least 1740 CDT as assessed subjectively in real time by viewing the project radarscope. (The project radar data were not used quantitatively in this analysis.) By 1800 CDT the echoes were dissipating as they drifted to the W and SW, although there are no NEXRAD data for documentation purposes.

Twenty-three hygroscopic flares had been expended over 99 min while 95 AgI flares had been expended on 31 cloud passes over 96 min in the same area of clouds. This case was evaluated with the NEXRAD radar data by calculating the lifetime properties of the seeded and non-seeded cells until they merged with other echoes or dissipated. This is called the "short-track" analysis using the methods of Rosenfeld (1987). No cloud physics data are available for this case.

The summed rainfall for the period of seeding until the gap in the radar data is shown in Figure 8, where $Z = 300R^{1.5}$ was used to relate radar reflectivity (Z) to rainfall rate (R). Referring to the legend relating the color contours to rain depths, one can see the rainfall was heavy in the seeded area (i.e., azimuths between 210° and 260° at 60km to 90km from the radar). The rainfall was also heavy in cores elsewhere, so there does not appear to be anything unique about the area of seeding. The maximum radar-estimated rainfalls range up to 75mm at several locations over the map. The rain depths are underestimated at the NW end of the treated line because of the truncation of the radar data. A rancher under the seeded clouds reported a maximum of 100mm on his ranch.

Plots of maximum echo heights (Hmax) vs. maximum reflectivity (Zmax) and maximum echo heights vs. their total lifetime rain volumes are provided in Figures 9 and 10, respectively. The treated cells are identified as red dots. Clouds producing < 100 m^3 of rain volume are plotted as 0.1×10^3 m^3 on the logarithmic scale. Eight of the 20 tracked seeded cells were quite reflective and rain productive. There were a few unseeded echoes, however, that were just as strong, so one cannot determine whether and by how much the rainfall may have been enhanced by the simultaneous coupled seedings.

3. DISCUSSION AND CONCLUSIONS

Current studies underway by the authors in Texas and Thailand show unequivocally clouds with strong coalescence are the most rain-productive, especially if those clouds are supercooled. Such clouds will produce early freezing of the seeding-induced raindrops resulting in the formation of graupel which can grow in the invigorated updraft by accreting the resident cloud water. Thus, artificial seeding that imitates this natural process is likely to be successful in increasing the rainfall. Simultaneous use of hygroscopic agents at cloud base and AgI near the supercooled cloud tops was viewed as one possibility. The hygroscopic seeding would generate raindrops and the AgI would promote their early freezing.

It was this prospect that prompted the exploratory dual operational seeding on 11 August 1996. The test was highly successful operationally, but there is no proof of the efficacy of the dual seeding. Although the seeded clouds organized into strong rain-productive masses, the seeding signature relative to the natural background is not strong enough to constitute proof the clouds reacted differently by virtue of the seeding.

Contributing to this uncertainty are two potential factors. First, the natural clouds on this day likely had some natural coalescence and raindrops. This would decrease the hygroscopic seeding signature relative to the non-seeded clouds of the day. Second, we were not able to bring to bear enough measurement firepower for the documentation of this case. Not having in-cloud microphysical measurements was a distinct disadvantage. There is just so much that can be done with case studies identified in the context of operational seeding.

It is the collective weight of the evidence over several research case studies in conjunction with randomized experimentation that will ultimately demonstrate the efficacy of cloud seeding. Cloud and mesoscale models, which simulate natural processes realistically, are vital also for the discernment of seeding effects. Although much can be learned from "piggybacking" with operational seeding programs in some instances, there is simply no substitute for a dedicated research program.

4. ACKNOWLEDGEMENTS

This research was supported by the Texas Resource Conservation Commission (TNRCC) under Agency Order No. 582-8-104352. Our special thanks to Mr. George Bomar of the TNRCC for his encouragement during the course of these studies.

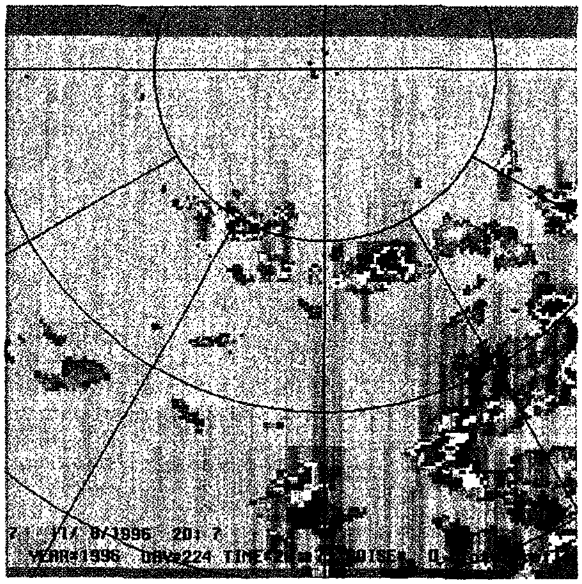


Figure 1. San Angelo PPI NEXRAD radar echo presentation at 2000 GMT on 11 August 1996. The color contours correspond to the following in dBZ: White > 60, light pink > 55, magenta > 50, orange > 45, gold > 40, yellow > 35, light green > 30, dark green > 25, light blue > 20, blue > 15, dark blue > 10, dark gray > 1, light gray > 0.

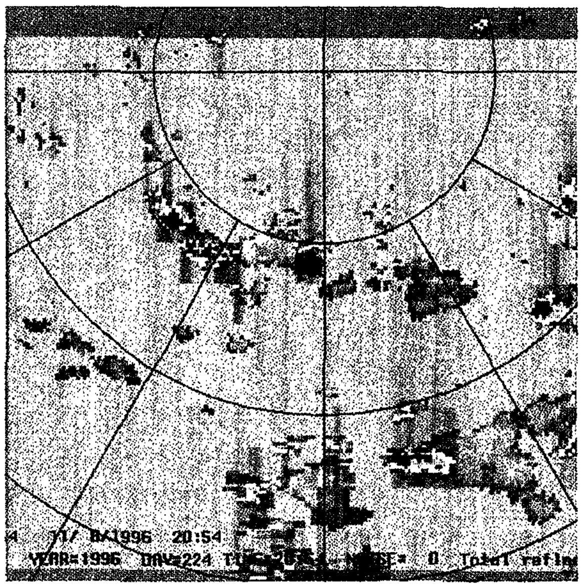


Figure 2. As in Figure 1 but for 2054 GMT.

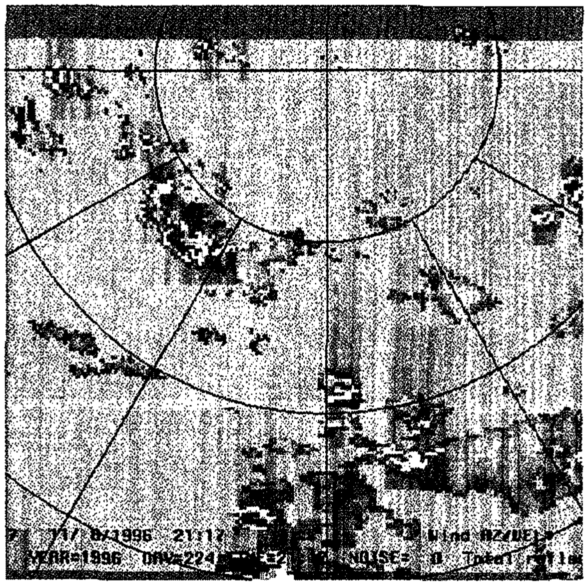
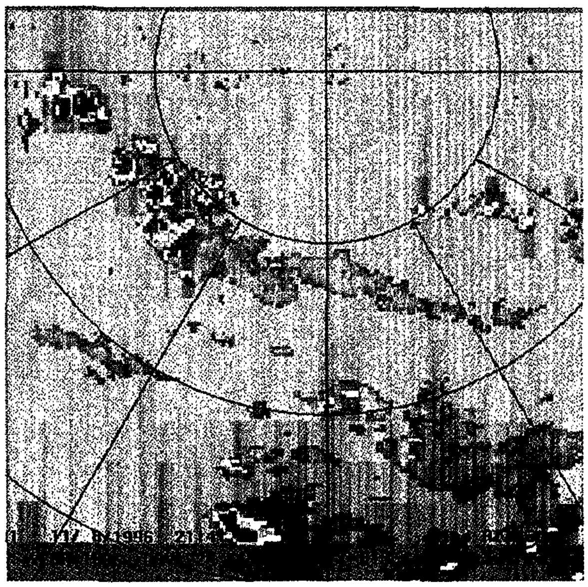


Figure 3. As in Figure 1 but for 2117 GMT



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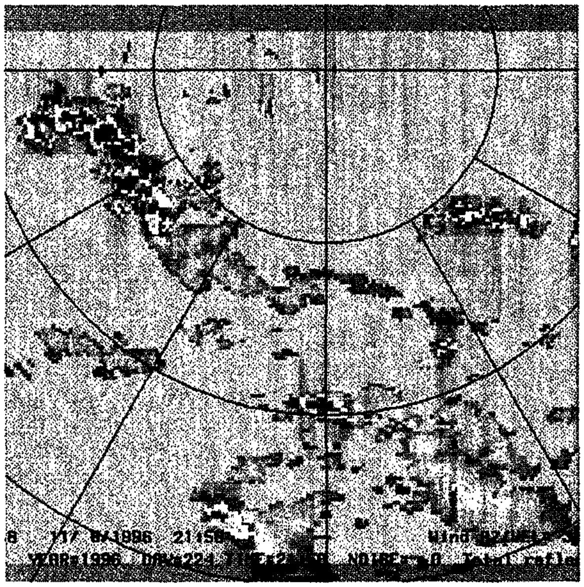

Figure 5. As in Figure 1 but for 2158 GMT.

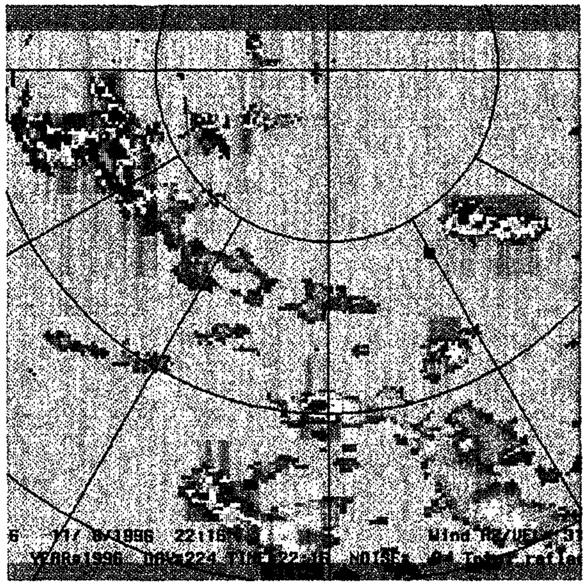

Figure 6. As in Figure 1 but for 2210 GMT.

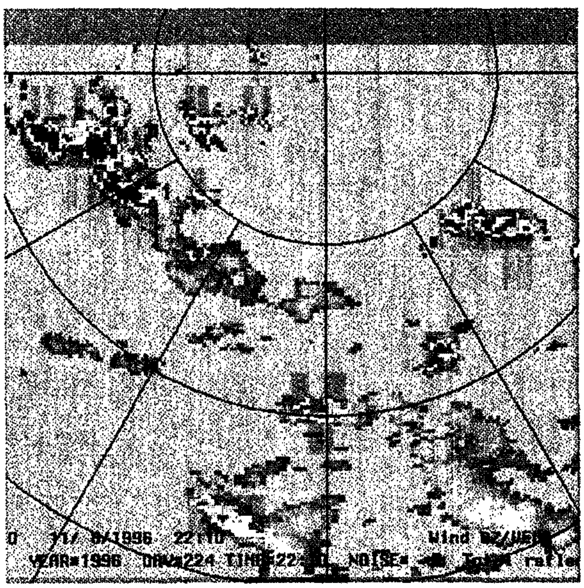

Figure 5. As in Figure 1 but for 2158 GMT.

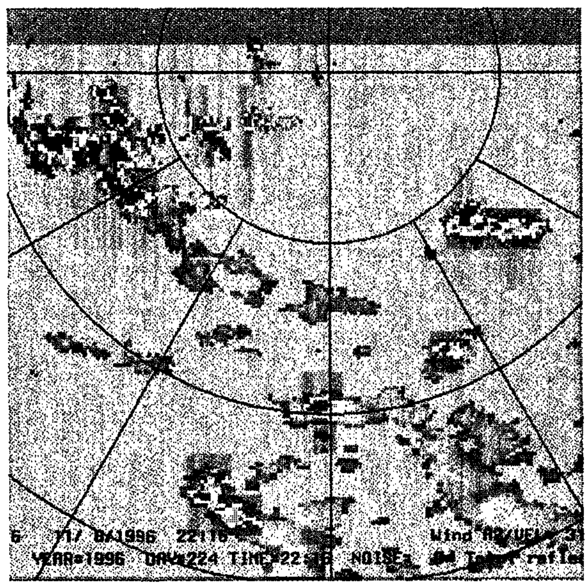

Figure 7. As in Figure 1 but for 2216 GMT. There are no radar data after this time.

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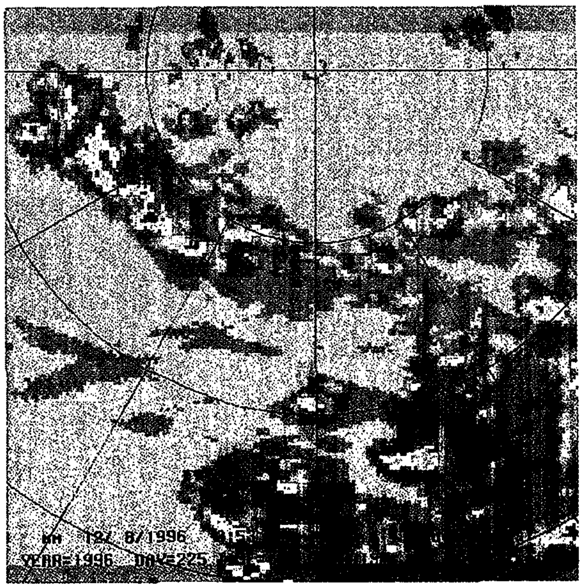

Figure 8. A summation of the radar-estimated rainfalls for the convective cells during the seeding period as discussed in the text. The color contours correspond to the following in mm: White > 150, light pink > 100, magenta > 75, orange > 50, gold > 30, yellow > 20, light green > 15, dark green > 10, light blue > 6, blue > 4, dark blue > 2, dark gray > 1, light gray > 0.

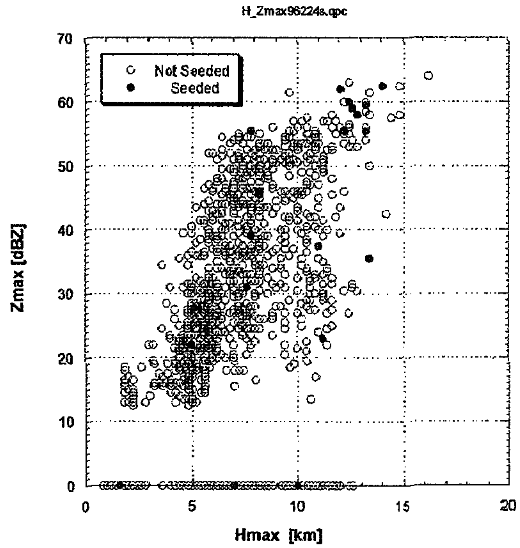

Figure 9. Scatter plot of the maximum height of the echoes (Hmax) vs. their maximum radar reflectivity (Zmax) for the seeded and non-seeded cells.

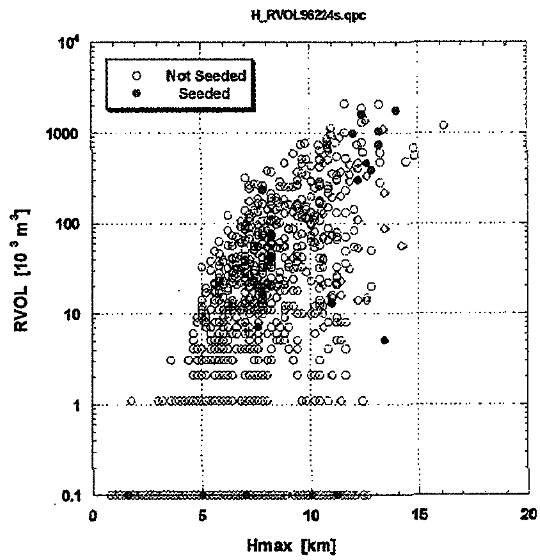

Figure 10. Scatter plot of the maximum height of the echoes (Hmax) vs. their total lifetime rain volumes (RVOL) for the seeded and non-seeded cells.

Comparison of Radar-Derived Properties of Texas Clouds Receiving One of Three Treatments: AgI Ejectable Flares or Hygroscopic Flares or No Seeding

William L. Woodley
Woodley Weather Consultants
Littleton, Colorado

and

Daniel Rosenfeld
Hebrew University of Jerusalem
Jerusalem, Israel

Abstract. Four clouds on 15 August 1996 provided an opportunity to observe and measure with radar their behaviors under various treatments: hygroscopic flares at cloud base, AgI flares near cloud top, indirect treatment with AgI ("secondary seeding") and no treatment. It was not possible to determine the expected behavior of the seeded clouds had they been left untreated, nor was it possible to reach any conclusions based on statistical analyses. Instead, the behaviors of the clouds were compared and interpreted based on physical reasoning. The cloud, which was seeded with 19 1-kgm hygroscopic flares over 43 min, was the tallest (14.9 km) and most rain productive (1,693 kilotons) of all of the clouds within scan of the radar. Based on this and other evidence, it is concluded that hygroscopic seeding may have been the most appropriate treatment for suitable clouds on this day. Because the cloud treatments were not randomized and in view of the known high natural variability of convective clouds in any region, this and other assessments presented herein must be viewed as speculative.

1. INTRODUCTION

Cloud seeding technology for rain enhancement has been under development in Texas for a number of years. The research is now being done under the acronym TEXARC (the Texas Exercise in Augmenting Rainfall through Cloud Seeding). This cloud seeding research has provided evidence for seeding-induced rain increases, which range from 100% for single clouds to 45% for rain over a floating-target area covering 2,964 km^2 (755 mi^2). The single cloud results are statistically significant at the 5% level. The area results for the 38 cases obtained to date are not statistically significant (Rosenfeld and Woodley, 1989; 1993; Woodley and Rosenfeld, 1996).

These research results, when coupled with analyses of two operational seeding efforts in Texas indicating increases in warm-season rainfall ranging between 25% and 40% (Jones, 1995; Woodley and Solak, 1990), have provided the justification for using cloud seeding in an attempt to mitigate droughts and to manage the water resources in Texas.

Not all Texas clouds are responsive to the same seeding technique and the same seeding agent. Just as physicians adapt their treatment to the needs of their patients, so too must seeding be adapted to the cloud conditions. On-top seeding with silver iodide flares as developed by the TEXARC research team of Woodley and Rosenfeld is thought to work best on vigorous convective clouds having some coalescence (Rosenfeld and Woodley, 1993). It apparently is not as effective on highly continental clouds containing very small supercooled cloud drops (Rosenfeld and Woodley, 1997). A different seeding technique and seeding agent is needed for these clouds.

Recent developments from experiments in South Africa suggest cloud-base seeding with hygroscopic flares may be effective in augmenting the rainfall from clouds that are not especially responsive to silver iodide seeding. Research by Mather and his colleagues (Mather et al., 1997) indicate that seeding with hygroscopic flares, producing tiny nuclei (average of 1 micron diameter) made up of potassium chloride and sodium chloride, produce changes in the clouds leading to earlier raindrop formation and increased rainfall.

Although there are some aspects of the results of Mather et al. (1997) that are still in question, there is reason to expect hygroscopic seeding as done in South Africa will enhance the production of raindrops in clouds and their subsequent rainfall. Confirming various aspects of the South African results now has high priority in TEXARC. Such confirmation would allow hygroscopic seeding to be used when the weather and cloud conditions are not suitable for seeding intervention with AgI.

The apparent increase in precipitation from the seeding of deep supercooled clouds at their bases with hygroscopic flares currently is thought to have been produced by the following steps (Mather et al., 1997 and personal communication with colleagues): 1) the introduction at cloud base of large and giant cloud condensation nuclei (CCN) produced by burning hygroscopic flares in racks mounted to the wings of the seeder aircraft, 2) preferential activation of the larger CCN from the flares, leading to a broadening of the cloud droplet distribution, 3) growth of the larger cloud droplets into raindrops via natural coalescence processes, in clouds which could not otherwise have "grown" raindrops through warm-rain processes, 4) the transport of the raindrops into the supercooled portion of the cloud where the raindrops freeze due to their larger size, 5) invigoration of the cloud due to the released latent heat and growth of the frozen drops to large graupel by accretion of the cloud water, and 6) increased radar-estimated rainfall at cloud base and presumably more rainfall at the ground, when the enhanced water mass moves downward through the cloud. Several of these links in the conceptual model guiding the hygroscopic seeding experimentation have not yet been documented satisfactorily. Providing such documentation through the analysis of case studies was the goal of TEXARC 1995 and 1996.

The case studies had the following objectives: 1) detect an alteration of the cloud-base droplet spectrum as a consequence of the seeding, 2) document a seeding signature in the form of anomalously large rain drops in the supercooled portions of the clouds, 3) detect a seeding signature in the radar data in the form of unusually high reflectivities and lower first-echo heights, 4) compare and interpret the radar histories on the same day of three comparable clouds which received different treatments (i.e., hygroscopic flare seeding, silver iodide seeding (AgI) and no treatment), and 5) analyze an operational seeding case in which the same clouds were seeded concurrently with hygroscopic flares at cloud base and AgI seeding near cloud top.

Rosenfeld and Woodley (1999) have addressed objective 1, concluding that, if hygroscopic seeding affects the cloud droplet spectrum, it occurs in its tail where the few large cloud drops are not detected by the FSSP instrument. Woodley and Rosenfeld (1999a) have addressed objective 2 in a case study in which huge raindrops (up to 8mm diameter) were detected following hygroscopic flare seeding. Objectives 3 and 4 are addressed in this paper and objective 5 is addressed in the companion to this paper (Woodley and Rosenfeld, 1999b).

2. RESULTS

Documentation of cloud development begins first on the mesoscale using the PPI and CAPPI data from the San Angelo NEXRAD radar (Figures 1a to 1n). At 2210 GMT (1710 CDT) the tiny first echoes associated with the clouds to be treated with AgI (marked by "A") and hygroscopic flares (marked by "B") can be seen about 45 km to the SSE and SSW. Twelve minutes later (7 min after initiation of hygroscopic seeding and 2 min before first AgI treatment) both echo masses had grown and intensified although maximum reflectivities had not reached 50 dBZ (Figure 1b).

At 2233 GMT the cell to the SSW receiving hygroscopic seeding was the stronger of the two with maximum reflectivities between 50 and 55 dBZ (Figure 1c). Another cell about 45 km to the WSW of the radar (marked by "C") is the unseeded cell of interest, which will be compared to the treated cells. Twelve minutes later the cell receiving hygroscopic seeding had a small reflectivity core > 55 dBZ while the cell receiving AgI seeding to the E had weakened and the unseeded cell farther W had intensified (Figure 1d).

At 2257 GMT the hyroscopically seeded cell was quite strong with maximum reflectivities > 60 dBZ. The unseeded cloud was also strong and the AgI-treated cloud was still weakening. New growth was evident to the N of the AgI parent (Figure 1e). Most of the AgI seeding took place along the upshear (North) feeders of the parent because this is where the clouds were most suitable. The directly treated cells did not grow much but debris from these cells likely provided secondary seeding for the larger parent.

By 2308 GMT (1808 CDT) the hygroscopic seeding had ceased and the cell was still quite strong on its NW edge. Cloud debris from all clouds was being exhausted to the S (Figure 1f). Both the unseeded and AgI-seeded cells had weakened although the cells to the N of the parent were growing. AgI seeding had ceased here 10 min earlier. All cells were weaker at 2320 GMT (Figure 1g). The cell that had received hygroscopic seeding was still the strongest of the three but the clouds receiving AgI had the longest N-S extent with the strongest cell on the N edge. The unseeded cloud (at "C") was the weakest of the three.

The weakening of the clouds was continuing at 2332 GMT with the cloud receiving hygroscopic flare seeding still the strongest by far (Figure1h). This trend continued through 2343 CDT (Figure 1i) but by 0001 GMT (1901 CDT) a new echo mass had formed in the debris from the two seeded clouds (Figure 1j) and remained strong through 0031 GMT (Figures 1k and 1l). Whether the growth of this new cloud was enhanced by ingesting ice debris from the dying clouds (i.e., secondary seeding), is not known. All of the cells of interest were dead by 0111 GMT (Figures 1m and 1n).

A summation of the radar-estimated rainfalls for the duration of the cells is provided in Figure 2. The wettest area was where the clouds had received hygroscopic seeding. It had two cores of up to 75 mm of rain (3 inches). The second most productive rain area was associated with the cell that may have been seeded secondarily from cloud debris from the treated cells. Examination of the very low rain totals as evidenced by the gray-black shading suggests this cell was most affected by the debris from the AgI-seeded area since this cell appears to have been intersected by the easternmost of the two parallel plumes streaming SSW from the two seeded areas.

The third and fourth most productive rain areas were associated with the clouds that were seeded directly with AgI and with the cloud that was never seeded. The unseeded cloud had the highest point rainfall but the rainfall from the cells treated directly with AgI covered more area. Although one can hardly claim seeding effects based on one case, we find typically the main effect of AgI seeding is to increase the areal coverage of rainfall and not its point maximum (Woodley et al., 1999c).

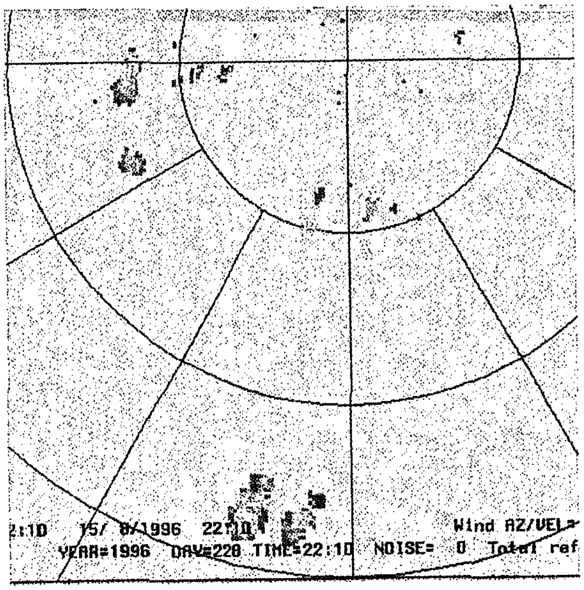

Figure 1a. San Angelo PPI NEXRAD radar echo presentation at 2210 GMT on 15 August 1996. The color contours correspond to the following in dBZ: White > 60, light pink > 55, magenta > 50, orange > 45, gold > 40, yellow > 35, light green > 30, dark green > 25, light blue > 20, blue > 15, dark blue > 10, dark gray > 1, light gray > 0.

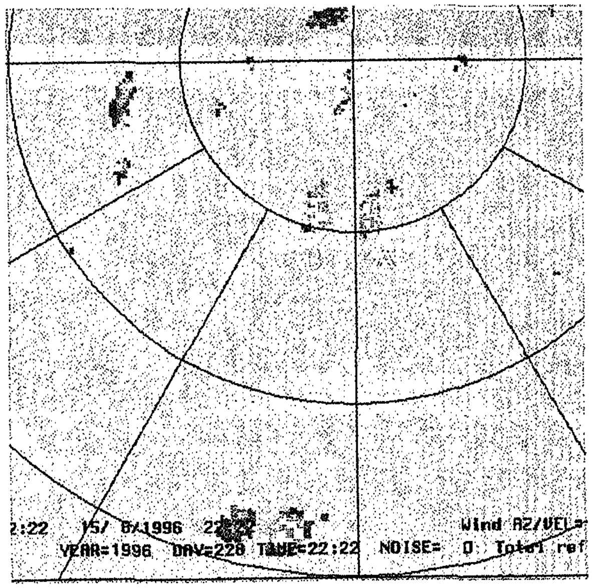

Figure 1b. San Angelo PPI NEXRAD radar echo presentation at 2210 GMT on 15 August 1996.

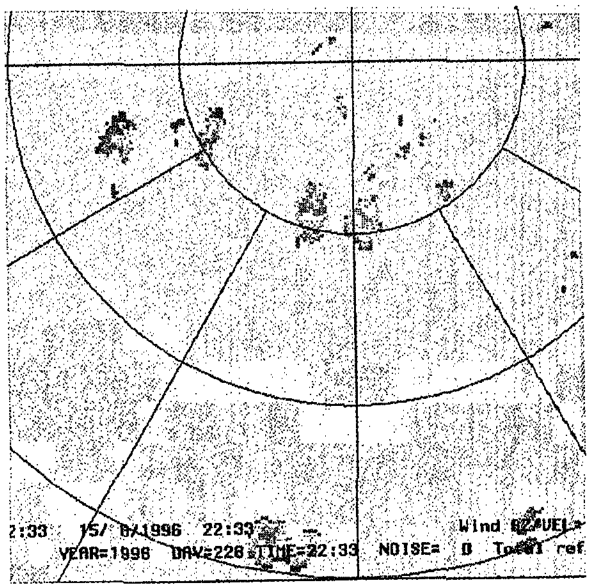

Figure 1c. San Angelo PPI NEXRAD radar echo presentation at 2233 GMT on 15 August 1996.

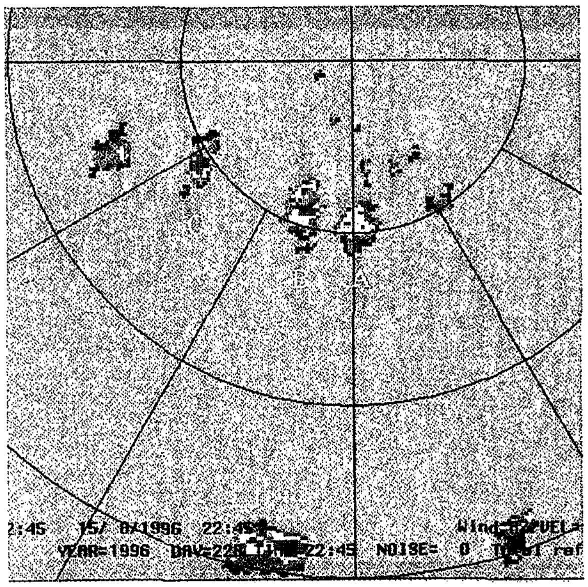

Figure 1d. San Angelo PPI NEXRAD radar echo presentation at 2245 GMT on 15 August 1996.

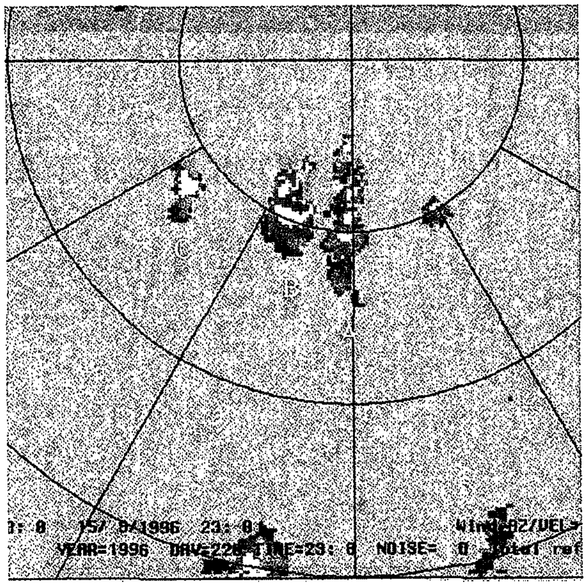

Figure 1f. San Angelo PPI NEXRAD radar echo presentation at 2308 GMT on 15 August 1996.

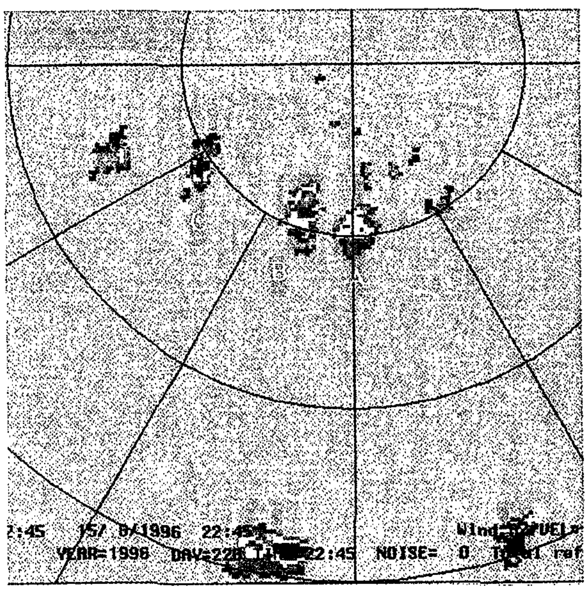

Figure 1e. San Angelo PPI NEXRAD radar echo presentation at 2257 GMT on 15 August 1996.

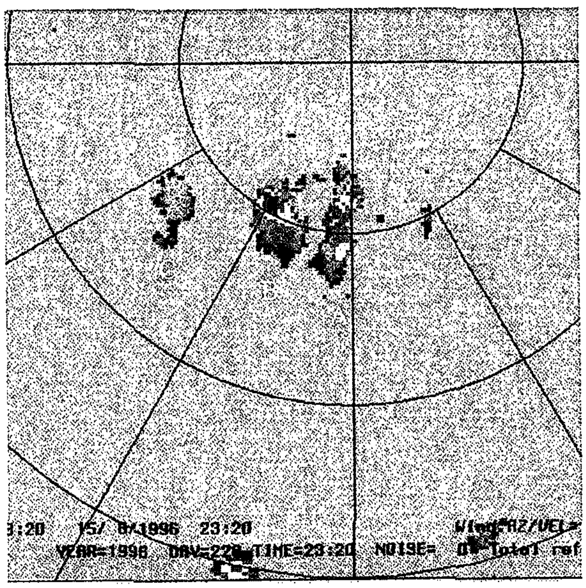

Figure 1g. San Angelo PPI NEXRAD radar echo presentation at 2320 GMT on 15 August 1996.

The next step was to focus on the lifetime properties of the individual cells as shown in Table 1. Listed are the cell number and a description of whether it received treatment directly or possibly indirectly through secondary seeding. Following this is the cell duration (min), its maximum height (Hmax in km), reflectivity (Zmax in dBZ), area (km^2) and rain volume (10^3 m^3). The cells are listed in numerical order. The cell properties were

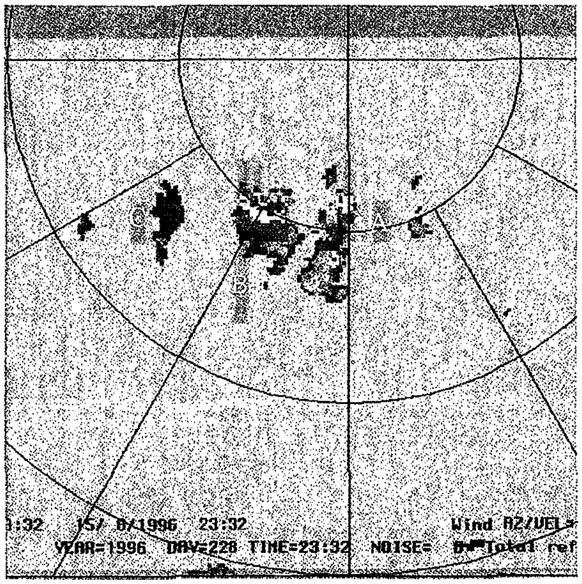

Figure 1h. San Angelo PPI NEXRAD radar echo presentation at 2332 GMT on 15 August 1996.

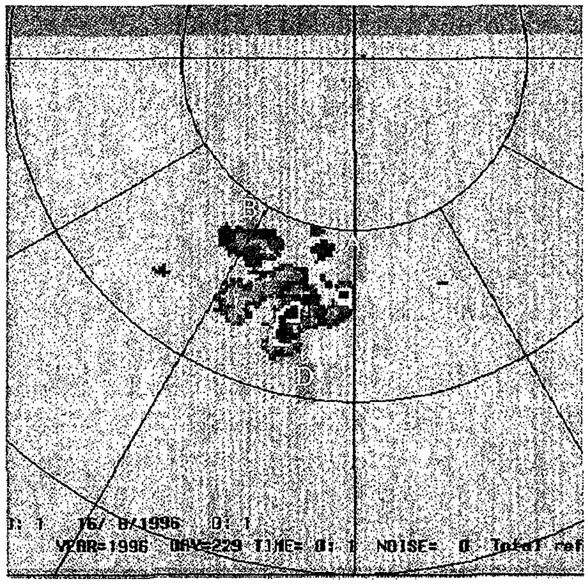

Figure 1j. San Angelo PPI NEXRAD radar echo presentation at 0001 GMT on 16 August 1996.

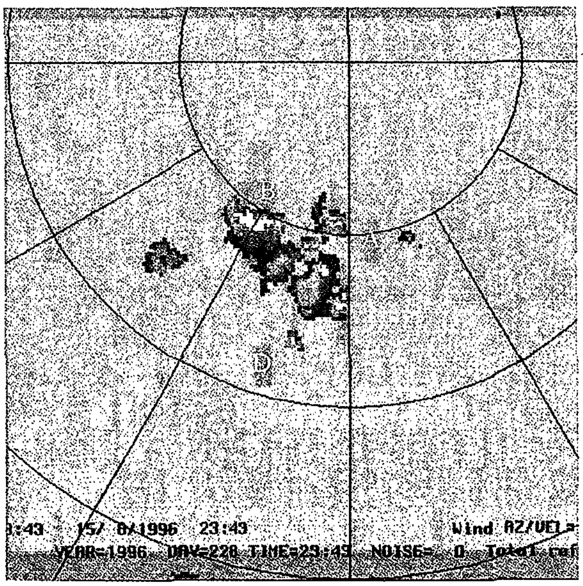

Figure 1i. San Angelo PPI NEXRAD radar echo presentation at 2343 GMT on 15 August 1996.

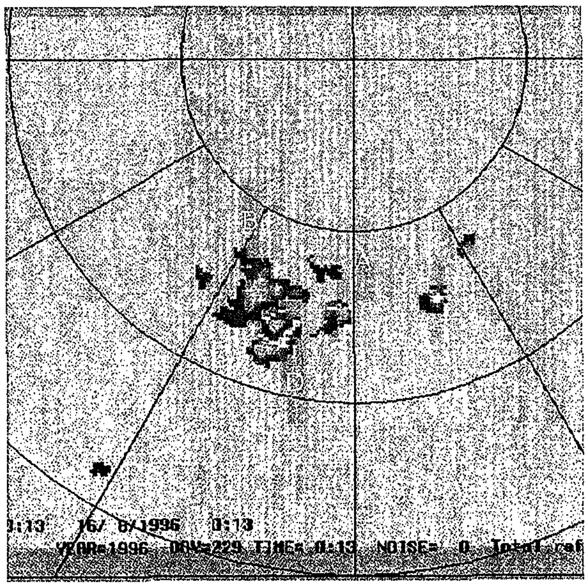

Figure 1k. San Angelo PPI NEXRAD radar echo presentation at 0013 GMT on 16 August 1996.

obtained using the tracking software of Rosenfeld (1987).

Of all the cells listed the cell receiving hygroscopic seeding cell 6826 was by far the most reflective, reaching 65 dBZ near cloud base, 60 dBZ at 7km, 50 dBZ at 11km height and a maximum echo height of 14.9 km. The AgI seeding started on small towers in cells 7390, 7771 and

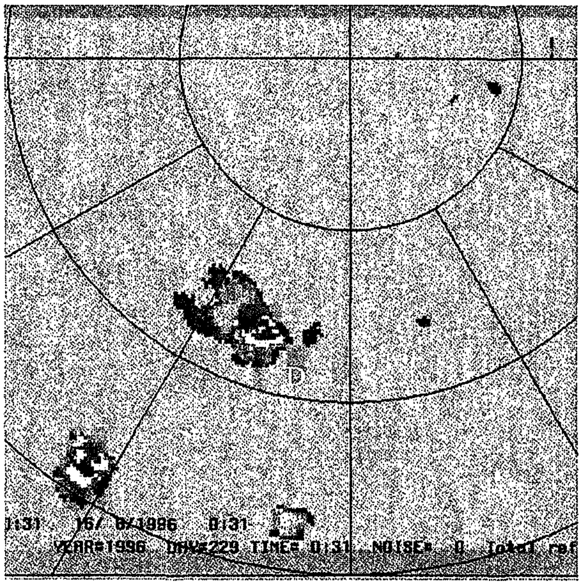

Figure 1l. San Angelo PPI NEXRAD radar echo presentation at 0031 GMT on 16 August 1996.

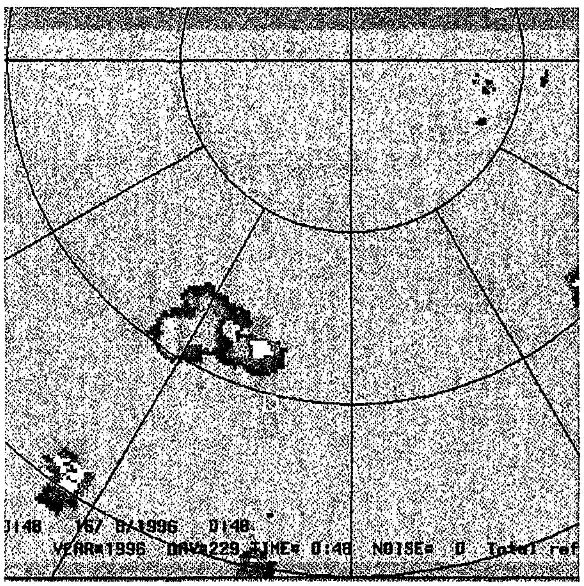

Figure 1m. San Angelo PPI NEXRAD radar echo presentation at 0048 GMT on 16 August 1996.

7976 upshear on the N edge of the main natural cloud (cell 5240). These small cells were short lived and weak. They produced downwind streamers that likely seeded cell 5240 indirectly. This cell produced 3.7 times less rainfall than the cell receiving hygroscopic seeding and was 4.5 km shorter in stature. The unseeded cell to the W of the two seeded cells (cell 7077) was comparable in size and rain production to the indirectly AgI-seeded cell but was more reflective.

The other cell of interest (Cell #6654) appeared to form in the debris downwind of the AgI seeded cell. It produced the second most rainfall of the day and was highly reflective and covered a large area. There is no way of knowing whether the ingestion of ice debris from the earlier directly-seeded cloud ("secondary seeding") may have played any role in the development of Cell #6654.

Plots of Hmax vs. Zmax and Hmax vs. RVOL for these cells with all of the cells of the day (in green) in the background are provided in Figures 3 and 4. It is readily obvious in the plots that the cell receiving hygroscopic seeding is anomalous relative to all of the other cells. It was the tallest,

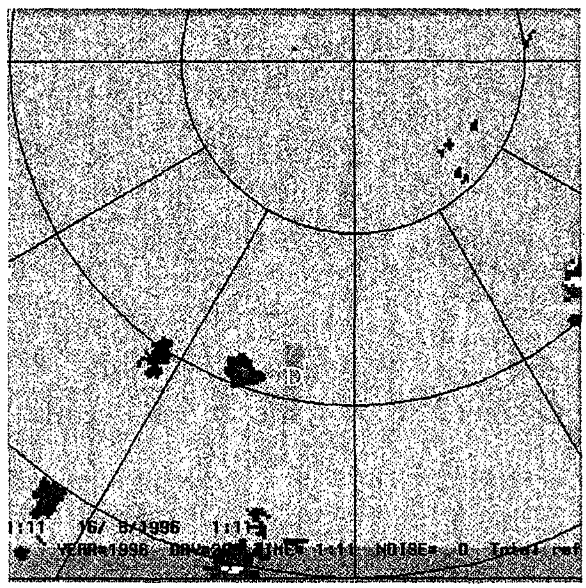

Figure 1n. San Angelo PPI NEXRAD radar echo presentation at 0111 GMT on 16 August 1996.

Table 1

Cell Lifetime Properties on 15 August 1996

Cell #	Cell Description	Duration (min)	Max Ht (km)	Max Z (mm^6/m^3)	Max Area (km^2)	RVOL ($10^3 m^3$)
5240	Main AgI cell	140	10.4	52.5	102.2	453
5695	Hygro fragment	17	4.2	38.5	10.7	1
6199	Unseeded Cell	41	10.0	47.0	45.8	43
6426	Unseeded Cell	35	10.0	47.0	45.8	43
6618	Unseeded Cell	6	4.6	19.0	5.3	0
6654	Dwnd AgI Cell	187	10.8	59.5	196.0	1238
6826	Hygro Cell	111	14.9	65.0	156.1	1693
6860	Unseeded Cell	29	6.0	35.5	36.8	8
7077	Unseeded Cell	70	11.2	59.0	124.9	471
7390	AgI fragment	18	4.8	30.0	8.9	1
7771	AgI fragment	12	5.0	19.0	6.1	0
7782	Unseeded Cell	41	8.2	51.0	47.6	86
7976	AgI fragment	6	5.4	0	0	0
8644	AgI & hygro Cell	12	11.2	34.0	96.6	19
9693	Unseeded Cell	76	11.0	50.0	112.2	143
0275	Unseeded Cell	58	10.6	54.0	86.3	250

clearly the most reflective, and produced the most rainfall. It seems possible, therefore, that the hygroscopic seeding may have contributed to the development of this cloud.

The time plots of properties for the main four cells listed in Table 1 are provided in Figures 5 through 8. The plots are given in the same order as in the table. Reference to the plot for the main hygroscopic cell (#6826) shows the cell reached 60 dBZ about 20min after commencement of seeding and stayed above 60 dBZ for 33 min. No other cell showed such a behavior.

The cell which grew in the debris of the AgI treated cloud (#6654) also had an interesting history. It existed as a weak entity for 90min before it took off and grew into a strong storm, lasting for 90 minutes thereafter.

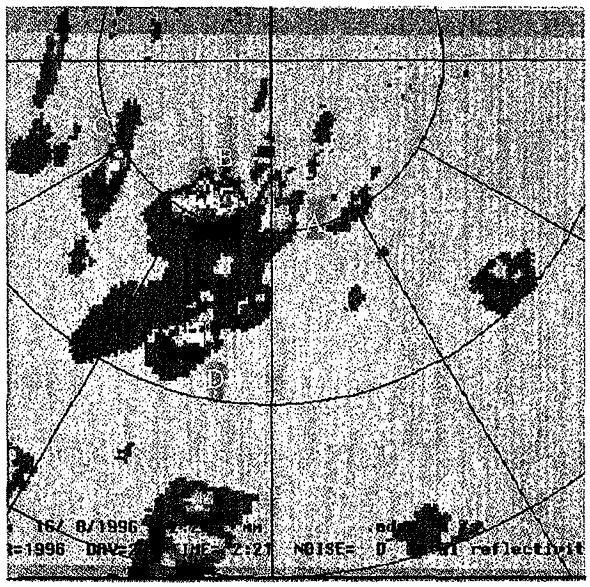

Figure 2. The radar-estimated rainfalls (mm). The color contours in mm: **Pink** > 100, magenta > 75, orange > 50, gold > 30, yellow > 20, **light** green > 15, dark **green** > 10, light blue > 6, blue > 4, **dark blue** > 2, dark gray > 1, light gray > 0.

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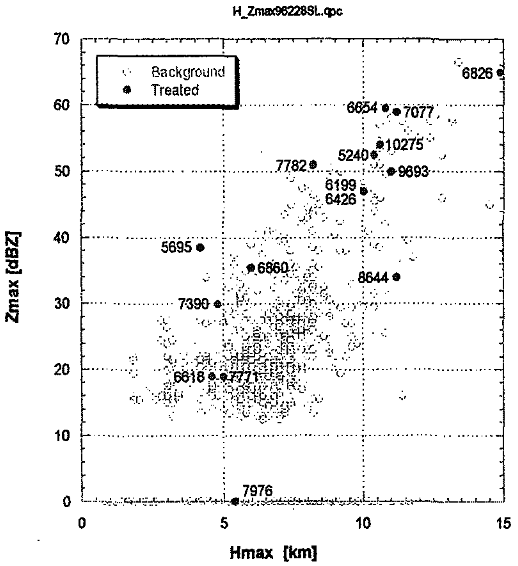

Figure 3. Scatter plot of the maximum height of the echoes (Hmax) vs. their maximum radar reflectivity (Zmax). The red points identify the direct or indirectly treated cells while the green circles correspond to the other echoes of the day within 159 km of the San Angelo NEXRAD radar.

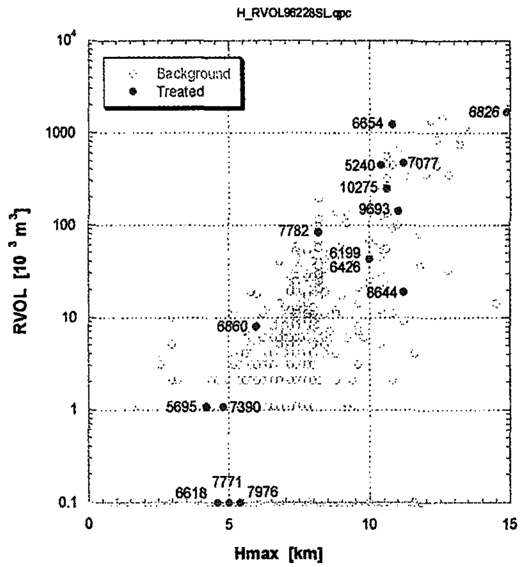

Figure 4. Scatter plot of the maximum height of the echoes (Hmax) vs. their total lifetime rain volumes (RVOL). The red points identify the direct or indirectly treated cells while the green circles correspond to the other echoes of the day within 159 km of the San Angelo NEXRAD radar.

3.0 DISCUSSION

Four clouds, which were not selected randomly for study, have been examined. All had echo tops between 5 and 6.5 km when they were treated. The one seeded with hygroscopic flares proved to be the most vigorous of the four with the highest maximum reflectivities and echo tops and the most volumetric rain production. The uncertainty is whether seeding was causal in its development.

We agree with Mather and his colleagues that hygroscopic seeding may work best when applied to supercooled convective clouds. If the seeding promotes the formation of raindrops in vigorous clouds, some of these drops will freeze when they are carried above the freezing level, because large drops freeze more readily than do small drops. This will release latent heat which will invigorate the cloud and spur additional growth while the frozen raindrops grow further into large graupel by accreting the supercooled cloud water resident in the updraft. This aspect of the hygroscopic seeding conceptual model as applied to supercooled clouds bears a strong resemblance to some of the links in the AgI seeding conceptual model. The key is the freezing of the raindrops, regardless of whether they have been produced naturally or artificially. Supercooled maritime convective clouds do this naturally and produce heavy rainfall. Seeding, whether it be hygroscopic or AgI, is intended to imitate these efficient natural processes.

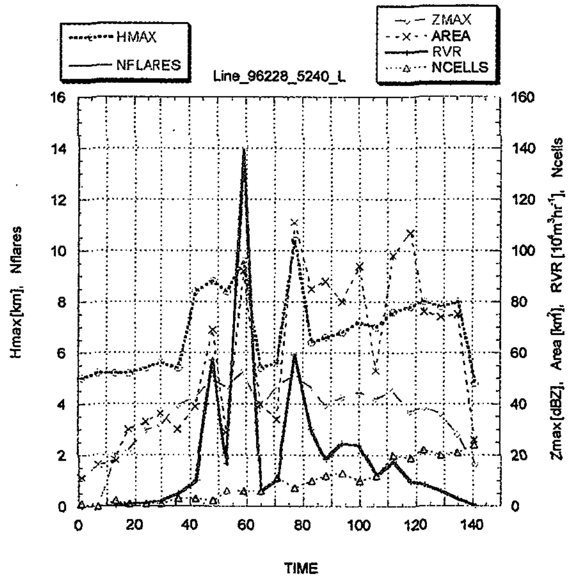

Figure 5. Line plots of the properties of cell 5240, which was seeded secondarily by ingesting AgI and/or ice particles from cells seeded directly on its upshear (North) flank. The cell properties and their units are as shown.

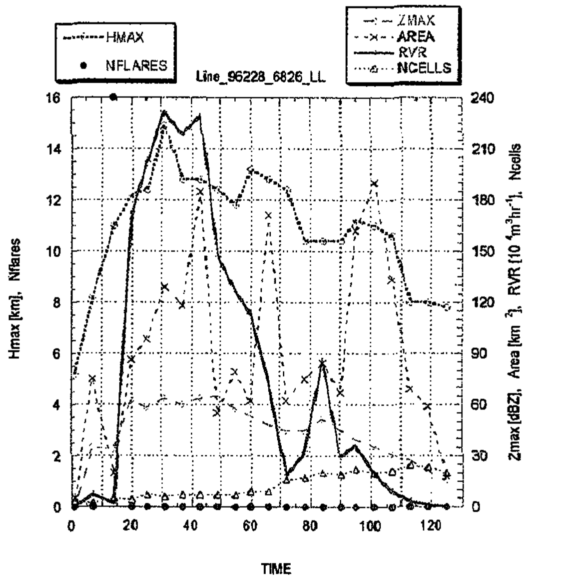

Figure 7. Same as Figure 5 but for cell 6826, which was seeded directly with 19 1-kgm hygroscopic flares at its base.

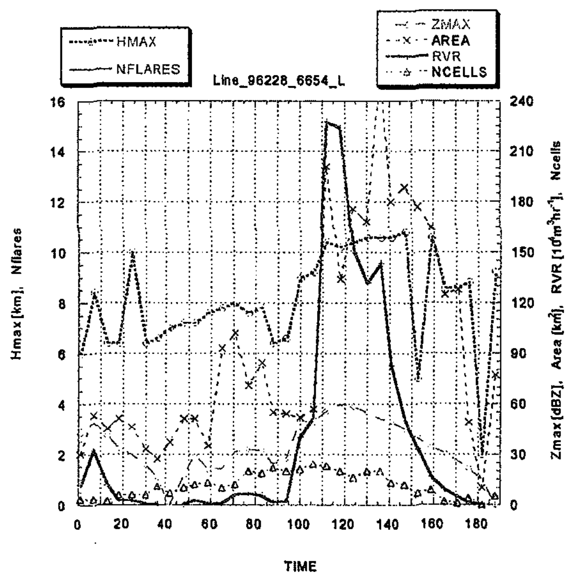

Figure 6. Same as Figure 5 but for cell 6654, which formed downwind of the directly seeded cells to its north. It appears as though cell 6654 grew through the debris from cell 5240.

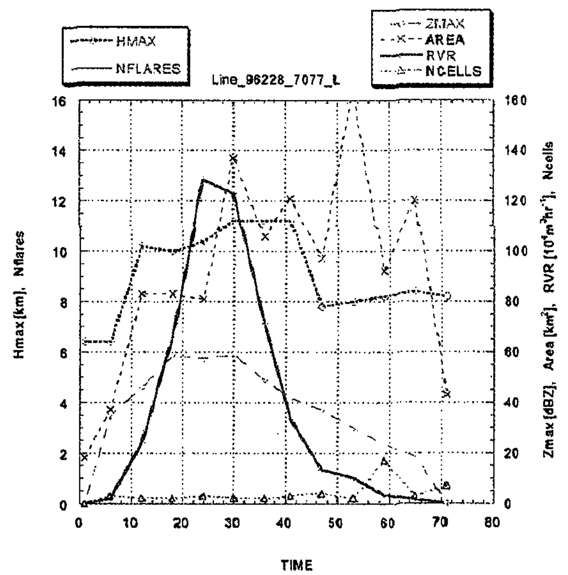

Figure 8. Same as Figure 5 but for cell 7077, which never received any treatment.

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A potential problem for radar evaluation of a cloud seeding experiment, whether it be AgI seeding or hygroscopic flare seeding, is seeding-induced alteration of the raindrop spectrum causing the radar to "see" more rainfall than the non-seeded clouds than is really there. This uncertainty was addressed by Cunning (1976) in the context of the Florida Area Cumulus Experiment, which tested the efficacy of AgI flare seeding for the enhancement of rainfall. Cunning measured the size spectrum of the raindrops from AgI-seeded and non-seeded clouds and found seeding did not alter the size spectra of the raindrops below cloud base. Seeding was found to produce more ice in the AgI seeded clouds. If AgI seeding also had produced changes in the particle size spectra in the upper supercooled portion of the clouds, these alterations apparently were eliminated by adjustment of the size spectrum through droplet breakup in the large depth of cloud below the level of seeding. Thus, radar-inferred differences in rainfall from seeded and non-seeded clouds should still have been valid.

Scientists associated with hygroscopic flare seeding assume Cunning's results are applicable to their research because their clouds have depths comparable to those in Florida. There is reason now to question, however, whether Cunning's results are applicable to hygroscopic flare seeding as practiced currently. If hygroscopic seeding were to affect only the tail of the distribution and produce only a few large drops, it is possible these drops could survive intact without breakup to cloud base. Non-seeded clouds would not have such large drops and this could result in an overestimation of the effects of seeding because of the dominance of large drops on the measured radar reflectivity and on the inferred rainfall.

Both authors participated in the experiments of 15 August 1996. The first author was on the cloud-base aircraft and did the hygroscopic seeding while the second author was on the ground and watched (but without a camera!) the development of the three clouds to the SSE-SW of San Angelo. Both individuals reported independently that the rain shaft from the cloud seeded with hygroscopic flares had a different appearance from the rain shaft from the AgI-treated cloud immediately to the E of the hygroscopic cloud. The rain shaft from the AgI cloud was thick and dark, blocking completely the background, while the shaft from the hygroscopic cloud was translucent such that it was possible to see the background through it. This suggests the size distributions of the raindrops from the two clouds were different. In such case, the radar would "see" the clouds differently even if the rainfall amounts were identical.

Had the cloud physics aircraft been available on August 15, 1996, the raindrop spectra from the seeded (AgI and hygroscopic) and non-seeded clouds would have been measured and the first step taken toward resolving this issue. The best we can do is report the dramatic visual differences in the rain shafts from the AgI and hygroscopically-seeded clouds. Such impressions hardly constitute proof, however, the raindrop spectra were different and resolution of this matter must await field measurements.

These case studies also raise the issue of secondary seeding, whereby unseeded clouds ingest ice particles from previously seeded clouds. We speculate it is very important to the propagation of seeding effects in space and time long after the direct seeding has ceased. We have already documented the reality of secondary seeding on the cloud scale in Texas. One such case was obtained in TEXARC 1998. The data show the glaciation of a cloud tower, which contained high concentrations of ice particles and no cloud water following AgI flare seeding. A new cloud tower high in cloud-water content later grew up and enveloped the old seeded tower. Aircraft penetrations of this new cloud showed high concentrations of ice (> 600/L) throughout its high cloud-water (4 gm/m^3) content region. Good photographic documentation exists for this case on the tape from the aircraft forward-looking video camera.

Assessing the impact on a field of clouds of secondary seeding, which might result also from hygroscopic flare seeding, is probably beyond our observational capabilities. When realistic cloud and mesoscale models exist, it is recommended they be used to assess the direct and indirect effects of seeding in the context of the conceptual model guiding the seeding experiments. The use of such models for the planning, evaluation and interpretation of the seeding experiments will prove to be crucial to their success.

4.0 CONCLUSIONS

The study of the four clouds receiving different treatments (AgI flares near cloud top, hygroscopic flares at cloud base, indirect treatment and no treatment) proved useful even though the treatments had not been randomized. The cloud seeded with hygroscopic flares "out performed" the other three by a large margin and was anomalous relative to all other non-seeded clouds within scan of the radar. It is concluded, therefore, that the hygroscopic seeding likely played a role in its development. The possibility exists, however, the radar-estimated rainfall from this cloud may have been overestimated due to an undocumented seeding-induced change *in its raindrop spectrum relative to the other* clouds.

These case studies also raise the issue of "secondary seeding" in the development of clouds, whether seeded or not seeded. It may provide a means of propagating the effects of seeding in space and time long after seeding has ceased.

5. ACKNOWLEDGEMENTS

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COALESCENCE ACTIVITY IN TEXAS CLOUDS: THE INDEX OF COALESCENCE ACTIVITY AND FIRST-ECHO TOPS

Aldis Strautins
West Texas Weather
Modification Association
San Angelo, Texas

Todd Flanagan
South Texas Weather
Modification Association
Pleasanton, Texas

William L. Woodley
Woodley Weather Consultants
Littleton, Colorado

Abstract: This paper explores the use of the Index of Coalescence Activity (ICA) as a tool for operations and evaluation in Texas rain enhancement programs. Radar cross-sections through the first echoes were used to find the heights using the TITAN display software package from two WSR-74C 5-cm radars located in San Angelo and Pleasanton, respectively. Index of Coalescence Activity values were derived using the morning sounding data from three upper air stations. The ICA vs. the average height of First-echo Tops (FET) for a particular day was then plotted with calculated correlation coefficients of 0.62, 0.51, and 0.38 for the Del Rio, Corpus Christi, and Midland stations, respectively. The results show generally good agreement between the observed first-echo height and the Index of Coalescence Activity predicted First-echo Top except in one case, which is addressed in the text. The results of this study warrent continued research and preliminary use of the Index of Coalescence Activity as a forecasting and an evaluation tool in the cloud seeding operations of Texas.

1. INTRODUCTION

Perennial questions in all enhancement programs are whether, when, where and how cloud seeding is to be conducted. A question being faced currently in some of the Texas programs that have decided to employ hygroscopic seeding for rain enhancement in addition to conventional AgI methods is when either AgI or hygroscopic seeding is to be employed. This decision should be based on the cloud characteristics and seeding criteria. Based on current thinking, hygroscopic seeding should be used in clouds without an active coalescence process and AgI seeding should be used in clouds with some coalescence. Poor results might be expected if AgI is used on days when artificial CCN should be used and vice versa. Further, optimal results might be expected by appropriately using two rather than a single seeding technique.

The conceptual model for cold-cloud seeding proposes the release of latent heat from the freezing of supercooled water droplets to provide energy to the updraft portion of the cloud. (For a more in depth explanation of the Texas cold-cloud seeding model see Rosenfeld and Woodley, 1997.) Forecasting for the presence of supercooled water drops at the seeding height of -8°C to -10°C (5.5 km to 6.5 km) for warm season convection in Texas is vital information for cold-cloud AgI seeding. As shown during the 1989 Precipitation Augmentation for Crops Experiment (PACE) the L coalescence parameter that was first introduced by Mather et al. (1986) and further refined by Czys and Scott (1993) as an Index of Coalescence Activity (ICA), was found to be a good indicator for the presence of supercooled water drops larger than 300 μm in diameter at the -10°C level. The PACE AgI seeding experiment, conducted in Illinois, used and evaluated the Index of Coalescence Activity as one of a number of tools used to forecast cloud characteristics of clouds to help in the recommendation of whether to seed or not seed on a particular day (Czys and Scott 1993).

The presence or absence of coalescence activity is also a major concern for hygroscopic seeding. Because hygroscopic seeding already is being employed at some places in Texas, it is appropriate to develop some guidelines for its use and evaluation. If the cloud tops are warm (i.e., > 0°C), hygroscopic seeding is the only option, if indeed any method is to be employed. If the tops are supercooled and loaded with raindrops, hygroscopic seeding is not the better choice. It makes no sense to seed to enhance coalescence and the formation of raindrops if natural conditions are already producing them in large concentration. Further, model simulations on hygroscopic seeding show no effect from the seeding of highly maritime clouds containing raindrops. It is important, therefore, to predict when the clouds will produce raindrops naturally and to diagnose in real time whether the clouds are producing raindrops naturally.

1.1 The Index Of Coalescence Activity

One way of predicting in advance whether the supercooled portions of clouds on a particular day will contain raindrops is to use the Index of Coalescence Activity (ICA), which was derived and used by Czys (Czys and Scott, 1993; Czys et al., 1996) from the work of Mather et al, (1986). Working in South Africa, Mather et al. (1986) showed that the presence or absence or supercooled drizzle and rain drops (> 300 microns diameter) at a temperature of about -10°C was related to cloud base temperature (CB_T) and the buoyancy at 500 mb (PB), where PB is defined as the temperature difference at 500 mb between the pseudoabiabat that runs through cloud base and the environmental temperature. From their data, Mather et al. (1986) determined a discriminator function, L, between clouds with supercooled drizzle and raindrops and those without, such that:

$$L = b_o + b_1 CB_T + b_2 PB \qquad (1)$$

Where the coefficients b_o, b_1 and b_2 were chosen to maximize differences between drops and no drops when L = 0 (Panofsky and Brier, 1958).

This relationship makes good sense physically because it indicates that coalescence is related to the length of time it takes an air parcel to rise from cloud base to the supercooled portion of the cloud. If CB_T is warm, the distance over which coalescence processes can operate within the parcel before it reaches the –10°C isotherm is large. PB implies an updraft speed. When the PB is large and positive, the air is unstable and the updrafts will be strong. Thus, when CB_T (distance) and PB (speed) are considered together, they represent a duration for coalescence. If the time is short, either because the updraft speed is large, cloud base is cold, or both, the likelihood that the cloud will produce drizzle and raindrops before the cloud top reaches the –10°C level is small. If the time is long for opposite reasons, coalescence will be active in the clouds and raindrops will be detected at the –10°C isotherm. In extreme cases, the time can be so long that coalescence takes place low in the cloud and the drops fallout, never reaching the supercooled portion of the cloud.

With the physics on a sound footing, Czys and Scott (1993) determined that the temperature at the convective condensation level (T_{CCL}) was a reasonable approximation for CB_T and made the appropriate substitution in equation (1). They then solved equation (1) for L = 0, using the plot provided by Mather et al. (1986), to obtain:

$$ICA = 8.6 - T_{CCL} + 1.72PB \qquad (2)$$

With this solution, negative ICA values are indicative of conditions when supercooled drizzle and raindrops are found in the clouds. If the ICA is strongly negative, the raindrop concentrations will be less because many of the drops will already have fallen from the clouds before reaching –10°C. When the ICA is positive, little, if any, supercooled drizzle and raindrops are expected in the clouds.

1.2 The ICA Related To Coalescence In Thailand

In addition to South Africa and Illinois, the ICA also was found to perform well in Thailand as a predictor of in-cloud coalescence activity as shown in Figures 1 and 2. Figure 1 is a scatter-plot from Sukarnjanaset et al. (1998) in which each plotted point represents ICA vs. either the median maximum or the mean maximum droplet or frozen droplet size in the supercooled portions (about-8°C) in Thai clouds. Thailand data are strictly aircraft measurements for both the droplet size and the cloud base temperature (CB_T). The correlation for the mean and median relationship are 0.65 and 0.66, respectively. Best fits to the mean (solid line) and median (dashed line) data are as shown. The results indicate that the droplet sizes increase as ICA decreases. Figure 2 is a scatter plot of visual estimates of in-cloud rainfall vs. ICA. Again it can be seen the in-cloud rain content increases as ICA decreases.

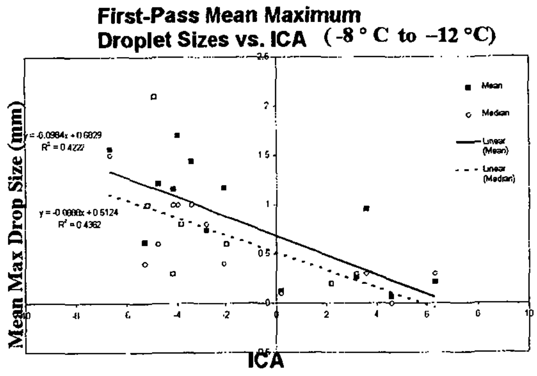

Figure 1. *Scatter-plot of the ICA vs. either the maximum median or mean for a droplet or frozen droplet size in the supercooled portions of Thai clouds (-8 °C). (Diagram is from Sukarnjanaset et al. 1998)*

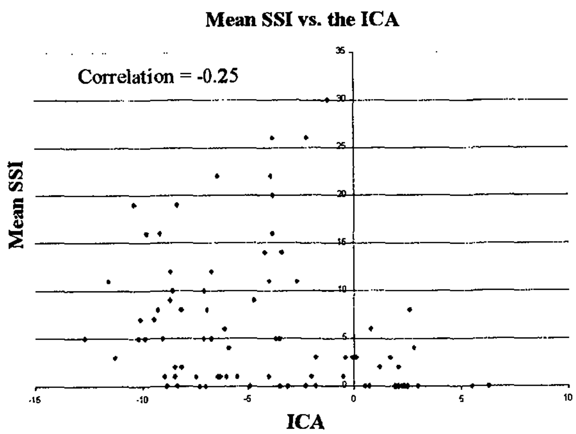

Figure 2. *Scatter-plot between ICA and the mean SSI values for days of experimentation in the Thai cold-cloud seeding experiments from 1993 through 1998. SSI are visual estimates of in-cloud rainfall.*

1.3 The ICA And Coalescence In Texas

The value of the ICA is being investigated in Texas by relating the Index of Coalescence Activity to the height of First-echo Tops (FET). First-echo Tops are used because: 1) first echoes should be indicative of coalescence activity, 2) aircraft data are not readily available, 3) it might afford the opportunity to use readily available radar data, and 4) the operational possibility of using FET as a tool to discern the type of seeding technique. Low First-echo Tops indicate active coalescence and the use of AgI might be appropriate where as high First-echo Tops indicate low coalescence activity and hygroscopic seeding might be a more appropriate method. The Index of Coalescence Activity has been calculated for 33 days during the 1998 season using the Midland and Del Rio soundings and for 34 days using the Corpus Christi soundings. The First-echo Top heights for the same days have been calculated using TITAN software with the San Angelo WTWMA and the Pleasanton STWMA WSR-74c 5-cm radars.

1.3.1 West Texas

The West Texas Weather Modification Association (WTWMA) has had an operational cloud seeding project in West Texas since 1996. The WTWMA consisted of eight full counties and a small portion of one county during the 1996 season. The total seeding coverage area for 1996 was just over 7 million acres. In 1997 the seeding area changed by one county to seven full counties and one partial county for a total of 6.4 million acres (Figure 3). Operations are run from the radar located at Mathis Field in San Angelo.

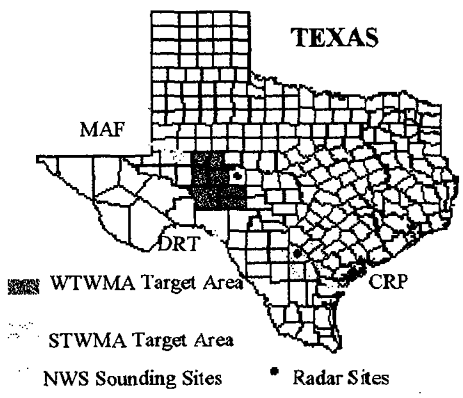

Figure 3. *Map of the WTWMA and STWMA target areas with related radar and NWS sounding sites.*

The climate of the seeding area for the WTWMA can best be described as a combination of both continental and sub-tropical. San Angelo is on the dividing line between the Texas Hill Country and the Edwards Plateau, the start of the West Texas desert. The northern portion of the seeding area is most represented by a continental regime with a sub-tropical regime influencing the southern portion. During the spring and early summer months fronts and/or drylines usually spawn convective activity. During the late summer and early fall seeding events are more likely to have a sub-tropical influence as tropical waves and/or storms from the Gulf of Mexico and Pacific moisture from the sub-tropical jet move through the seeding area.

The 1998 seeding season turned out to be an abnormal year. The spring and early summer had fewer than normal convective events, leaving West Texas with severe drought conditions. Mid summer was dominated by High pressure located over the center of Texas, making the general flow for West Texas southeasterly. By mid-August to mid-September a few tropical systems briefly helped to alleviate the southern section of the target area from severe drought conditions. Seeding operations were suspended on a number of these tropical events due to flooding potential. This tropical moisture stayed mainly south and east of San Angelo.

1.3.2 South Texas

The South Texas Weather Modification Association (STWMA) has been running a cloud seeding project in South Central Texas since 1997. During the 1997 and 1998 seasons, the South Texas project performed seeding missions over seven counties south of San Antonio. The project's WSR-74c radar is located in Pleasanton at the Municipal airport, where the seeding operations are run (See figure 3 in section 1.2.1).

The climate of the seeding area can best be described as sub-tropical with a modest continental influence. A southeast flow, common during the spring and summer months, brings in warm, moist air from the Gulf of Mexico. This is seen in the fact that dew points during the summer average in the mid-70's and occasionally approach 80 degrees. The sea breeze, especially prevalent in the area during the summer, is often a catalyst for shower and thunderstorm development, although other features can and do contribute to convective activity.

The 1998 season was not an average year for South Texas. Much of the spring and summer experienced severe drought conditions, and it was not until August when the weather finally became more active and the seeding opportunities increased. In fact, from August through mid-September, an MCS, two tropical storms, and a couple of tropical waves affected the area, resulting in self-imposed suspensions over a number of days because of the potential of flooding.

2. METHODOLOGY

Echo tops were chosen because they indicate the maximum elevation at which raindrops are present within the cloud. Also, echo tops are convenient to use and readily available making it easier to transition from a research to an operational cloud seeding program. On days when seeding occurred, the respective radar was closely monitored for first echoes forming within a 100 km radius of that radar. A radius of 100 km was used in order to include First-echo Tops that were at the 2 km level and above. The top of the 'first echo' was found by taking a cross-section through it and simply noting the height of the top of the echo. This is a convenient feature of the TITAN radar display software. For the days that the first-echoes met the above requirement, First-echo Tops were determined and the average was calculated. This average value was used as the First-echo Top for that particular day.

For the 1998 seeding season, the Index of Coalescence Activity was calculated for each day that seeding operations took place based on the 12:00 UTC sounding. Days on which the Index of Coalescence Activity could not be derived due to a) either bad or non-existing sounding data or b) when the T_{CCL} was above the 500 mb level were eliminated.

2.2 Sectoring The Radar In West Texas

Two NWS sounding stations are close to the WTWMA's rain enhancement program target area. They are Midland (MAF) and Del Rio (DRT). The 12 UTC morning sounding was used to determine the Index of Coalescence Activity for each station. The San Angelo radar was partitioned into two sectors; one toward each of the sounding locations in order to help distinguish between the continental and sub-tropical air masses. The MAF sector was defined as the 232-degree radial, from the WTWMA's San Angelo radar, to the 360-degree radial. The DRT sector was from the 112-degree radial to the 232-degree radial. First-echo Tops that were not observed within the 100 km radius, within the appropriate sector radials, or didn't form within the particular sector, were eliminated from the study.

2.3 No Sectoring Needed In South Texas

For South Texas, the morning sounding at Corpus Christi (CRP) was used to calculate ICA. Unlike San Angelo, the sounding from CRP was the only one used because it is to the Southeast of the target area, and as mentioned earlier, a southeast flow is predominant over the target area during a majority of the seeding season.

3. RESULTS

The Index of Coalescence Activity conceptually verifies with South Texas (CRP) having mostly negative ICA values, showing a tropical influence and West Texas (MAF) ICA values mostly positive showing a continental influence. The Index of Coalescence Activity values derived from the Del Rio sounding show, with little surprise considering it's location, the combined influence of both sub-tropical and continental air masses with a more even distribution of both positive and negative values.

3.1 Results For West Texas

Scatter plots between the index of Coalescence Activity (the abscissa) and the First-echo Tops (ordinate) have been constructed for Midland and Del Rio NWS soundings as shown in Figures 4 and 5 respectively, along with the linear correlation coefficients and best fit lines. The average ICA values for MAF and DRT were 4.3 and 1.35 respectively. The Midland ICA values show 28 positive to 5 negative out of 33 total values. Del Rio ICA values are 20 positive to 13 negative out of 33, suggesting that the southern portion of the WTWMA seeding area has the opportunity to utilize either AgI or hygroscopic or a combination of both. In the northern portion, hygroscopic seeding may be a useful method/mechanism for producing raindrops.

But these MAF ICA values do not seem to be representative of or relate to the average First-echo Top for the 1998-seeding season. The average FET for the MAF sector is 6.7 km, which would seem to be a little low for what one would expect from a 4.3 average ICA value. The correlation between ICA and FET is 0.38 for the MAF sector confirming that the MAF derived ICA values do not represent the observed First-echo Tops well.

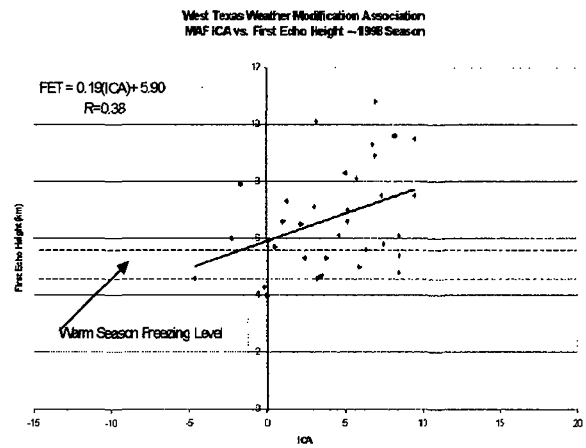

Figure 4. *Scatter-plot of ICA vs. FET for 33 seeded days in the 1998 season. The ICA is derived from the MAF 12 UTC sounding. The average FET is calculated using a cross-section from the WTWMA radar.*

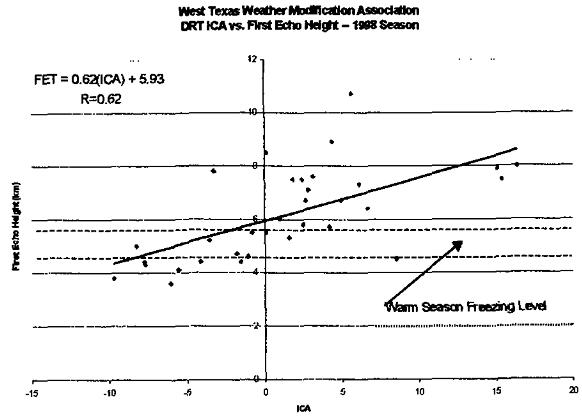

Figure 5. *Scatter-plot of ICA vs. FET for 33 days in the 1998 season. The ICA is derived from the DRT 12 UTC sounding. The average FET is calculated using a cross-section from the WTWMA radar.*

First-echo Tops and ICA values relate better for the DRT sector with average FET of 6.2 km. Note there is a positive correlation, 0.62, between ICA and the First-echo Tops. This means as ICA decreases the First-echo Tops decrease. For large negative ICA values the tops of the first echoes are less than 5 km in most instances, meaning the echoing portion of the cloud containing the raindrops is warmer than 0°C. It would be important to note at this point that the average freezing level in Texas runs between 4.5 and 5.5 km AGL. It is questionable whether hygroscopic seeding would enhance the rainfall from such clouds.

3.2 Results For South Texas

Figure 6 shows a scatter plot between ICA values (the abscissa) and the First-echo Tops (ordinate) that was constructed for the Corpus Christi NWS sounding, including the linear correlation coefficient and best fit line. It comes as no surprise that the vast majority of days in the South Texas project saw ICA values less than zero. The average ICA during the seeding period was -3.7 with 28 negative values and 6 positive values out of 34 total (two days have the same values). This would suggest that the clouds were naturally producing raindrops effectively, and that hygroscopic seeding would likely not produce a significant enhancement in the rainfall. To further support this, the average first-echo height during the 1998 season was 5.83 km AGL with a correlation between ICA and the FET of 0.51. Since the average warm season freezing level in South Texas runs between 4.5 and 5.5 km AGL, most of the cloud is warm, and most certainly contains raindrops.

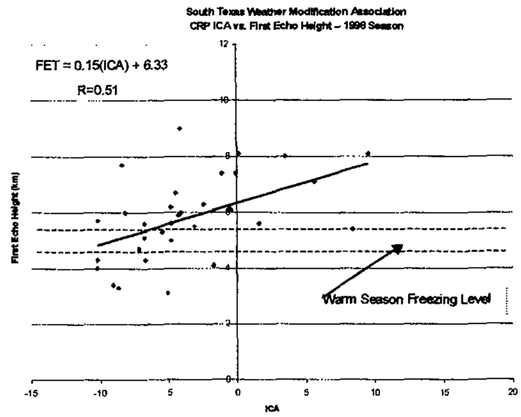

Figure 6. *Scatter-plot of ICA vs. FET for 34 seeded days in the 1998 season. The ICA is derived from the CRP 12 UTC sounding. The average FET is calculated using a cross-section from the STWMA radar.*

4. DISCUSSION

Because the behavior of FET is consistent with the hypothesis of increased coalescence activity with increasingly negative ICA, it should be possible to use the Index of Coalescence Activity to determine which type of seeding should be employed. We can surmise that when ICA is large and negative silver iodide seeding should be employed instead of hygroscopic seeding if seeding is to be done. As ICA increases, however, coalescence activity is weak at best and hygroscopic seeding should take precedence over silver iodide seeding. Regardless of which method is chosen at the outset, the decision should be checked using the First-echo Tops and perhaps checked again using in-could measurements of a candidate cloud. Whenever the First-echo Tops are low relative to the height of the 0°C isotherm, hygroscopic seeding is probably not the better choice regardless of the ICA. Silver iodide should be used in those circumstances assuming cloud heights rise above the –5°C level.

4.1 First-echo Tops And Hygroscopic Seeding Evaluation

A physical means of evaluating hygroscopic seeding is embodied in Figures 4, 5 and 6 in which First-echo Tops are plotted vs. ICA. If operational seeding is conducted on days when ICA is large and positive, the natural cloud First-echo Tops will be high and supercooled. By identifying a seeding area of effect on such days, one might look at the tops of the First-echo Tops in the presumed area of effect to determine whether they have been lowered in this area as a result of seeding. If no lowering is evident over the course of a number of seeding events, one would have reason to question the effectiveness of the hygroscopic seeding. On the other hand, if hygroscopic seeding is effective, the mean First-echo Tops as a function of ICA should be less than for clouds that did not ingest the hygroscopic material. This analysis will be pursued in the Texas evaluation effort.

4.2 The MAF Sector Correlation

During this study the events that had positive Index of Coalescence Activity values and lower FET than expected (according to the trend line) were looked at on an individual basis. Concerning the low correlation for the MAF sector three possible reasons were looked into. The first is that the air mass at the sounding station location was not representative of the air mass where and when the First-echo Tops were measured. The second reason is the First-echo Tops lowered as the new cells ingested water droplets from the older cells next to them. Thirdly, the temperature at the CCL (T_{CCL}) may not be a good representation of the actual cloud base temperature (CB_T).

The difference in air masses between Midland and San Angelo may have played a significant role in why the Index of Coalescence Activity had a difficult time predicting the FET and why the MAF correlation did not turn out well. Looking at the individual cases where the expected FET derived from the ICA value deviated greatly from the actual FET, it was found that there was a difference in the air mass between Midland and San Angelo. This was in the form of either a dryline/front or tropical system from the Gulf with San Angelo being in the warm and moist air mass.

In the spring there is a movement of moist air from east to west overnight and then a return back to the east during the daytime hours. By the time the afternoon thunderstorms develop and the First-echo Tops are measured the dryline has moved east. Also, on many days the dryline or front stalls between Midland and San Angelo where the moisture laden air will give lower FET than the Index of Coalescence Activity will predict in the dryer air of Midland. When the positive ICA values were greater than three (ICA > 3) and First-echo Tops were below 6 km, every case showed a difference in the air mass between Midland and San Angelo. The events in the spring and early summer mainly are due to a dryline or a front lying between Midland and San Angelo. (Sub-tropical events will be discussed later.) The dry air in Midland will give positive derived ICA values and therefore predicted high First-echo Tops. But the clouds would form in the moisture-laden air east and southeast of Midland returning lower actual First-echo Tops. In the relationship where the ICA values were greater than 5 but less than 10 and the FET were very large in height, over 9.0 km, a change was found in the air mass from the 12 UTC sounding to the time that FET started to occur. For example, a dryline progresses west to east during the day. The cells then develop in the dryer region of the air mass. This explains why the predicted FET were lower than the observed FET.

The late summer and early fall of 1998 had a number of tropical systems move into Texas bringing a tropical air mass to the target area. The tropical air mass stayed in the southern and eastern parts of the target area pushing into the MAF radar sector yet not all the way to Midland where the sounding is taken. This would account for getting low First-echo Tops for the MAF sector compared to higher ICA values and would in turn help explain the discrepancy between the two values and why the correlation between the two was low.

With respect to the second reason, a review of each of the cases for the MAF sector First-echo Tops showed the possibility that a few days could have been effected by ingesting water droplets from surrounding mature cells. By ingesting the water drops the new growth's first echoes would start lower in height. This effect can be seen more readily when cells are clustered. There were a couple of the large positive ICA and low first-echo height days in which the 'cluster effect' could be a possible cause of the low First-echo

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Tops. The 'cluster effect' may also explain the few events in South Texas when the CRP derived ICA predicted higher values than the actual First-echo Tops. More comprehensive analysis of this feature is being done on the 1998 season data and will be done in future years.

The radar was sectored to alleviate the differences between continental and sub-tropical air masses but it did not substantially reduce the differences for the 1998 season. Del Rio ICA values better represented the environment in the WTWMA seeding area for the 1998 season. When sectoring was eliminated, The DRT correlation between ICA and FET nominally increased to 0.64. As expected Midland's correlation remained low (< 0.40).

The third case concerning the low correlation for the MAF sector is that the T_{CCL} is not a perfect indicator of the CB_T. Due to the small 1998 data set of aircraft measurements preliminary analysis comparing the T_{CCL} with the CB_T is inconclusive. Further investigation is needed in this area.

5. CONCLUSIONS

Two types of air masses, continental and sub-tropical, affect the WTWMA target area. The data shows that the line between these two air masses tends to oscillate between Midland and San Angelo. The Index of Coalescence Activity vs. FET values for the MAF sector shows this to be true. This makes the forecast of First-echo Tops using the Index of Coalescence Activity derived from the MAF sounding less than straightforward. The overall weather pattern should always be considered, but special consideration should be taken were the dryline/front is positioned, or the influence of a tropical system from the Gulf of Mexico can significantly affect differences in the MAF ICA value vs. the FET.

The Index of Coalescence Activity derived from the DRT sounding proved to be a better representation of the air mass in the 112 to 232 radial sector as well as the seeding area as a whole with a correlation of 0.62 and 0.64 respectively. Although at times it can be seen that there is some variation in the ICA value and the FET for the 1998 season, the Index of Coalescence Activity derived from the DRT sounding looks to be a good indicator of coalescence at the -10°C level (i.e. the seeding level).

The Corpus Christi ICA values and the low First-echo Tops conceptually relate to the sub-tropical conditions that one would expect around the Gulf of Mexico. The Index of Coalescence Activity did an adequate job in predicting the FET considering that the radar sits over 175 km from the coast while the sounding station is on the coast, and a modest continental air mass can affect the seeding area without influencing the sounding station.

The number of positive vs. negative ICA values for each of the three stations shows that there may be good reason to have both cold-cloud and hygroscopic seeding methods available in Texas. This is especially true for a region that is influenced equally by both continental and maritime air masses.

A detailed study of the radar data for the 1998 season is in progress. Until this is complete, it remains unclear whether or not the Index of Coalescence Activity is a good predictor of seeding type for the Texas projects. However, there is enough positive evidence to advocate more research in regard to the use of the ICA vs. FET for evaluation purposes as well as an operational forecasting tool in Texas seeding projects. Further research is and will be designed to include: 1) the study of how representative the morning soundings are to the actual afternoon conditions, 2) how the 'cluster effect' relates to FET, 3) analysis of T_{CCL} to CB_T, 4) testing Mather's discriminator function at the -10°C level in Texas, and 5) a variation of the research done by Czys et al. (1996) involving a climatelogical analysis of the ICA in Texas. The study of the Index of Coalescence Activity with relation to First-echo Tops will thus continue in Texas.

6. ACKNOWLEDGEMENTS

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SUMMARY OF THE NOAA/UTAH ATMOSPHERIC MODIFICATION PROGRAM: 1990-1998

by Arlin B. Super
Bureau of Reclamation
Denver Federal Center

Abstract. This paper summarizes many previously published physical investigations into the artificial nucleation ("seeding") of winter mountain clouds in central Utah during 1990-1998. Program goals were to evaluate the effectiveness of the Utah operational cloud seeding program and to recommend improvements. Field programs employed a wide variety of instrumentation systems. Sophisticated numerical modeling was used in conjunction with the observational programs. Amounts and distributions of supercooled liquid water (SLW) cloud were investigated, as was transport and dispersion of ground-released seeding agents and tracer gases. Several experiments directly monitored ice crystals and snowfall rates resulting from either silver iodide (AgI) or liquid propane seeding. Results showed frequent SLW in excess of natural conversion to snowfall, suggesting significant seeding potential. The SLW was concentrated near the terrain where temperatures were relatively warm. When valley-released AgI was transported to cloud levels, resulting ice crystal formation was usually too limited for significant snowfall augmentation. However, marked enhancement of ice crystal concentrations and snowfall rates resulted from a number of high altitude releases of both AgI and liquid propane. Propane seeding was effective within even slightly supercooled cloud. Several recommendations were given for improving the operational seeding program's effectiveness.

1. BACKGROUND AND INTRODUCTION

1.1 General Background

The purpose of this article is to summarize in one place the most important results of many previously published articles and conference papers. These resulted from a multi-year project investigating the effectiveness of winter orographic (mountain-induced) cloud seeding in Utah, with emphasis on the Utah operational seeding program. This applied research was primarily sponsored by the National Oceanic and Atmospheric Administration (NOAA) Atmospheric Modification Program (AMP), in cooperation with the Utah Division of Water Resources and the Bureau of Reclamation (Reclamation). Discussions of the multi-state AMP are given by Reinking (1992) and Golden (1995). While the Utah portion of the NOAA AMP (hereafter NOAA/Utah AMP) began several years earlier, the cooperative program discussed herein began late in 1989 when Reclamation became involved. Reclamation scientists continued to participate in the NOAA/Utah AMP through 1996, at which time NOAA AMP funding was terminated by the U.S. Congress. Some additional analyses were performed after 1996 as reflected in this article.

A total of 29 journal articles and conference papers were published under this program during 1992-1998. These publications resulted from research done by a number of groups involved in the program during this decade. In addition to Reclamation, those groups included the University of Nevada Desert Research Institute (DRI), the University of North Carolina at Asheville, the University of Utah, Utah State University, the National Center for Atmospheric Research (NCAR) and North American Weather Consultants (NAWC). The NOAA Environmental Research Laboratories in Boulder, Colorado, also had a major role in this program. This agency provided an instrumented cloud physics and plume tracking aircraft for two major field programs, including pilots and technical personnel needed to support the sophisticated instrumentation systems. Their support was crucial to the program's success.

1.2 Objectives and Research Reported

The research reported herein is based on the last several years of the NOAA/Utah AMP when field work was conducted on the Wasatch Plateau (Plateau) of central Utah, approximately between the towns of Fairview and Price. Earlier work was conducted on the Tushar Mountains of southern Utah. That work, which has its own large body of publications (e.g., Huggins and Sassen 1990), is not discussed in this report. The single exception is the article by Sassen and Zhao (1993) which is quite relevant to the Plateau findings and was published during the Plateau phase. A review of the earlier years of NOAA AMP work, with an extensive list of references, is given by Reinking (1992).

The NOAA/Utah AMP had two main objectives during the period in question. First, the program was designed to *physically* evaluate the effectiveness of the Utah operational seeding program which has been partially funded by the State of Utah. Second, the program was to recommend to the Utah Division of Water Resources any changes which might improve future effectiveness of the operational seeding program. The operational program's goal was to increase the high mountain snowpack, which should lead to spring and summer streamflow augmentation (Super and McPartland 1993). Numerous findings and recommendations which could improve the operational program are to be found in the articles and papers summarized herein. Any decisions to implement such recommendations are the responsibility of the Utah Division of Water Resources and cooperating local water management agencies which jointly fund the operational program.

The key physical questions addressed during the studies reported herein are listed below and repeated in section 7.2.

1. When, where, and in what quantities does SLW exist within orographic clouds in excess of that naturally converted to mountain snowfall?

2. When, where, and in what quantities does the seeding agent affect the SLW cloud, converting portions of it to embryonic ice particles? In Utah, the operational seeding agent has been AgI produced by valley generators using the acetone-silver iodide-ammonium iodide solution.

3. When, where, and in what quantities do the seeding-induced ice crystals grow to snowflake sizes and fall to the mountain surfaces?

Most of the investigations reported during the NOAA/Utah AMP addressed one or more of the above questions. Section 7.3 briefly states the key physical findings to these questions.

1.3 Problems with Statistical Evaluations

Three statistical evaluations of the operational program have been reported by Thompson and Griffith (1981), Griffith et al. (1991), and Griffith et al. (1997). The reader is referred to these articles for details of the operational program which used valley-based silver iodide (AgI) generators, typically spaced on the order of 16 km (Griffith 1996). A small minority of all generators were sited in or near canyon mouths which could help transport and dispersion over mountainous terrain.

While all three of the statistical evaluations have suggested seasonal snowfall increases in the 10-20 percent range, one should be very cautious about accepting such indications. Griffith et al. (1997) correctly point out their (statistical) techniques, "are not as rigorous or scientifically acceptable as is the randomization technique used in research." A sizeable body of literature exists which discusses the many difficulties of after-the-fact statistical analysis of operational seeding programs and why such attempts should be viewed with caution. Dennis (1980) and Gabriel (1981) discusses some of the many problems that can result from improperly applied statistical approaches. Most of these arguments will not be repeated here. However, a major problem is the lack of any randomization with operational seeding programs, considered by many statisticians and meteorologists as essential for valid statistical testing. Target-control analysis of the type applied to Utah's operational seeding program must assume that precipitation relationships are stable over decades. This assumption presents a major difficulty (Dennis 1980), especially in view of known climatic change. In the Utah analyses, these relationships are assumed stable over long distances, from central and southern Utah target precipitation gages well into Nevada and Arizona where control gages were selected. But it is well known that precipitation relationships can change over time and space for a variety of reasons ranging from large scale climatic changes to local changes in the environment of a precipitation gage (e.g., growth of vegetation affecting gage catch). Another problem with the cited Utah statistical analyses is that markedly different sets of control gages and target gages were used in each analysis. Some changes in gage selection may be necessary as gages are discontinued or relocated. But whatever the reason, any changes in target and control gages after the initial selection (which should have been made prior to any seeding) diminishes the credibility of statistical results.

Because of these and other problems with post-hoc statistical analysis of the Utah operational program, the Utah Division of Water Resources agreed that physical evidence was needed to evaluate the operational program. Accordingly, the NOAA/Utah AMP was heavily based on physical observations and reasoning, including sophisticated numerical modeling.

1.4 Selection of Wasatch Plateau Experimental Area

Soon after Reclamation became involved in the NOAA/Utah AMP, observational emphasis was shifted from the Tushar Mountains of southern Utah to the Wasatch Plateau of central Utah. This shift in the experimental area occurred because of several practical considerations, which significantly improved field observations. A winter field program was conducted during early 1990 on both the Wasatch Plateau of central Utah and the Wasatch Range just east of Salt Lake City (Super and Huggins 1992a, 1992b). Both are long north-south mountain barriers which should minimize transport of valley-released seeding material around them. However, the Plateau offered several advantages for field observational studies including less rugged terrain which permitted in-cloud aircraft sampling much closer to the barrier top, and all-weather roads across and along the Plateau, permitting widespread surface sampling by instrumented vehicles and access to fixed installations.

The importance of low-level instrumented aircraft sampling and instrumented vehicle sampling along the Plateau's all-weather highways, cannot be overemphasized. It has simply not been practical to obtain such observations for other mountain regions, with a few exceptions like the Grand Mesa of western Colorado (Super and Boe 1988). Aircraft sampling over the Plateau was conducted under special waivers from the Federal Aviation Administration. This procedure allowed flight to within 300 m of nearby *highest* terrain, while standard flight rules require 600 m minimum separation over mountainous terrain. Moreover, lowest sampling passes were made in a terrain-following mode, rather than flying at a constant altitude (Super 1995a), which required exceptional flying and navigational skills by the NOAA pilots. This practice and the special waivers resulted in lowest aircraft observations within 600 m of typical (not highest) Plateau top elevations. *In spite of the unusually low level sampling, the aircraft could not always descend into ground-released seeding plumes or significant SLW cloud because both were in shallow layers over the terrain.*

The relative uniformity of the Plateau, with the broad Sanpete Valley to the west and parallel San Pitch Mountains farther westward, provided simplicities for airflow trajectories and numerical modeling efforts compared with more complex and rugged terrain. Nevertheless, the Plateau is believed to be reasonably typical of most of Utah's north-south oriented mountains targeted by the Utah operational seeding program.

Figure 1 shows the frequently investigated portion of the Plateau. Highway 31 ascends the Plateau's west slope from the town of Fairview on the Sanpete Valley floor. It splits into two all-weather roads (31 and 264) at the western edge of the Plateau top. From that intersection highway 31 follows the Plateau top's west (upwind) edge for several kilometers to the south and southeast. This portion of highway was frequently sampled by instrumented vehicles, and significant fixed surface instrumentation was located next to the highway. One major aircraft track was generally above this portion of highway 31, and extended well north and south of it, following the Plateau top's west edge. Both highways cross the entire Plateau top permitting along-the-wind sampling.

1.5 Experimental Field Projects

During the years under discussion, three limited and two major field programs were conducted. The limited, early 1990 program was conducted on the Wasatch Range and Wasatch Plateau, as discussed by Super and Huggins (1992a, 1992b).

Major field programs were held on the Plateau from mid-January to mid-March of both 1991 and 1994. Major equipment used during these programs included:

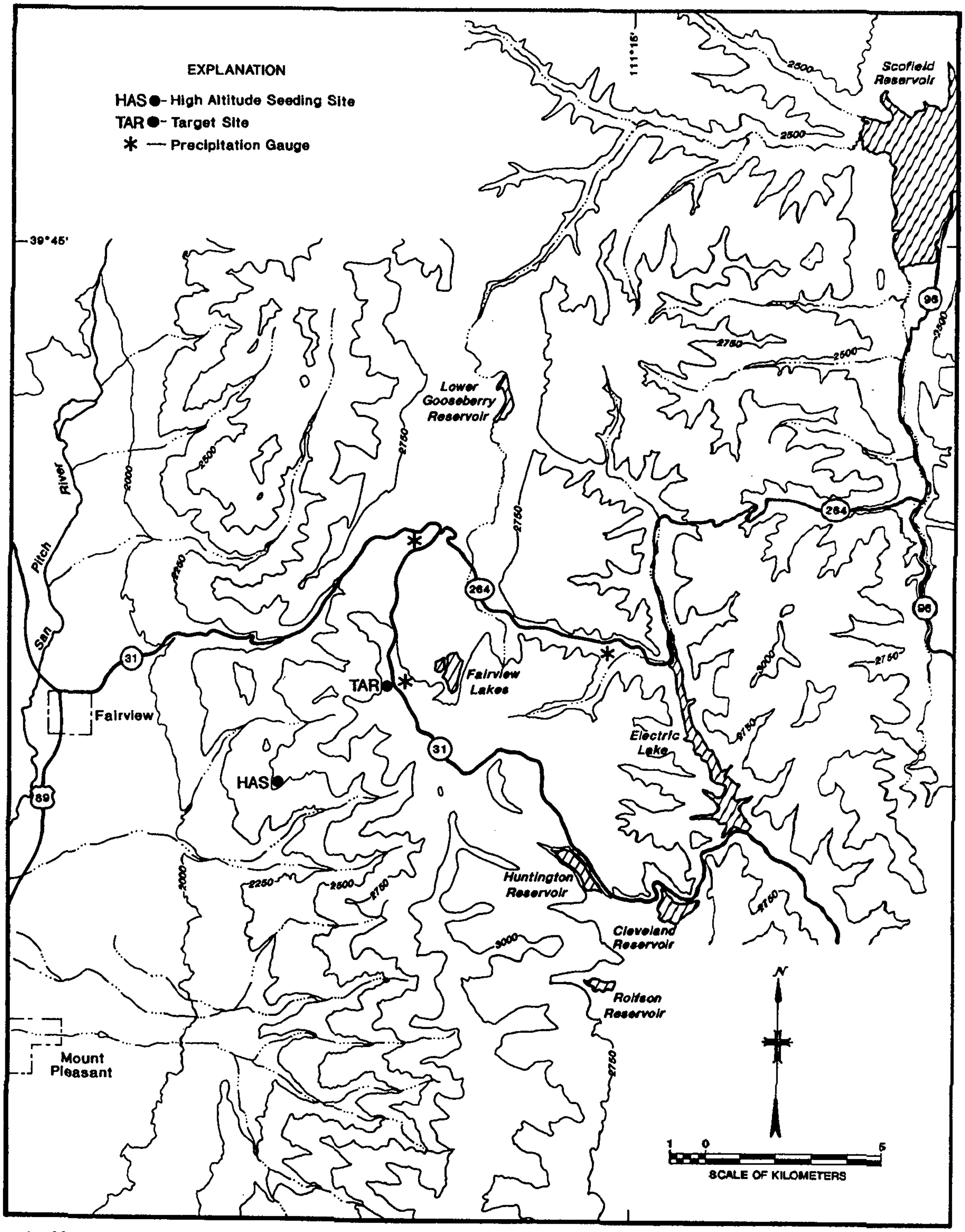

Fig. 1. Wasatch Plateau Experimental Area in central Utah showing terrain contours in meters above sea level. The towns of Fairview and Mount Pleasant are shown in the Sanpete Valley west of the Plateau. All-weather highways 31 and 264 provide access over the Plateau. The several kilometer portion of highway 31 just south and southeast of its intersection with 264 was used for frequent surface sampling along the Plateau top's west (windward) edge. The Target site (TAR) and High Altitude Seeding Site (HAS) were used in the 1994-95 and 1995-96 winter experiments.

- The NOAA Beechcraft King Air C-90 (N46RF) cloud physics and plume detection aircraft
- fixed and mobile microwave radiometers for monitoring vertically integrated liquid water and water vapor
- weather radar
- fixed and mobile ground-based detectors for silver iodide (AgI) and sulfur hexafluoride (SF_6) tracer gas
- valley and high altitude AgI seeding generators and SF_6 release equipment
- recording precipitation gage networks
- local rawinsonde releases in the Sanpete Valley
- automated weather stations

More information on these programs is provided in several articles summarized herein (e.g., Super 1994, 1995a).

Limited field programs took place on the Plateau during the 1994-95 and 1995-96 winters. These programs used a single, high altitude release site with AgI and SF_6 release capabilities and automated weather observations (HAS on figure 1). A single target to detect the effects of seeding was operated on the west edge of the Plateau top (TAR on figure 1), as discussed by Super and Holroyd (1997). The target station was equipped to observe AgI, SF_6, ice particle characteristics (by 2D-C laser probe), and supporting weather information.

1.6 Structure of Article

This article is made of 7 sections followed by references. This first section presents an introduction and background information. Section 2 discusses the availability of supercooled liquid water while section 3 concerns the transport and dispersion of ground-released seeding agents and tracer gas. Section 4 presents the results of physical cloud seeding experiments and section 5 discusses numerical modeling investigations. Miscellaneous associated work is found in section 6 and, finally, section 7 contains a summary and several recommendations for improving the operation seeding program.

The original published form of the 29 articles and papers summarized herein would total hundreds of pages of text and figures, for it is a significant body of work. In addition, numerous project reports and field program operations plans were produced during the NOAA/Utah AMP. This additional information is not discussed here.

2. AVAILABILITY OF SUPERCOOLED LIQUID WATER

2.1 Background Information

It is well known that a necessary (but not sufficient) condition for winter orographic cloud seeding to be effective is the availability of SLW in excess of that naturally converted to snowfall. Successful seeding also requires transport and dispersion of seeding agents into the SLW clouds in sufficient concentrations to convert significant quantities of SLW to ice particles. Moreover, the conversion must take place where sufficient time and distance permit ice particles resulting from seeding to grow to snowflakes sizes which settle to the mountain surface before sublimating in the lee subsidence zone. All of this must happen in an ever-changing and complex airflow and cloud environment. While it is sometimes convenient to consider winter orographic clouds as quasi steady-state entities, they actually change rapidly over a wide range of spatial and temporal scales.

Many operational winter orographic cloud seeding programs and a number of experimental projects have assumed the presence of abundant SLW. However, few programs have made significant efforts to test this *crucial assumption*. The NOAA/Utah AMP put considerable effort into investigating spatial and temporal SLW distributions, using both observations and sophisticated numerical modeling. Indeed, documentation of SLW was the program's first major scientific objective.

Several of the studies summarized herein dealt with the important topic of SLW. These include Huggins (1992), Sassen and Zhao (1993), Super and Huggins (1993), Super (1994), Huggins (1995), Super (1995a), Huggins (1996), and

Wetzel et al. (1996). Observations of SLW were made by tower-mounted icing rate meters, sensors carried by the NOAA instrumented aircraft, and by both fixed and mobile microwave radiometers. A mobile microwave radiometer was first deployed in the field during the NOAA/Utah AMP, as discussed by Huggins (1992, 1995) and Wetzel et al. (1996). It proved invaluable in mapping SLW distributions over the Plateau.

The general portrayal of SLW over the Plateau in the articles just noted is similar to findings from other mountainous regions, as reviewed by Super (1990). He noted that, "There is remarkable similarity among the research results from the various mountain ranges. In general, SLW is available during at least portions of many storms. It is usually concentrated in the lower layers, and especially in shallow clouds with warm tops. Average integrated amounts are normally limited implying low cloud liquid water contents, in agreement with aircraft observations."

The articles cited herein agree with the Super (1990) portrayal and expand upon it. Seasonally, a significant portion of the SLW flux is not converted to snowfall during passage over the Plateau. This finding suggests the availability of sufficient "raw material" for seeding to have an important impact on snowfall, *provided that seeding can convert a significant portion of the SLW flux to snowfall.* The seasonal SLW flux is concentrated in a few large storms that are efficient snowfall producers during portions of their passages but inefficient during other phases. Super and Huggins (1993) considered the SLW flux across a number of mountain barriers. They concluded that seeding may be appropriate both when SLW is abundant and when it is more limited. The relatively rare hours with large SLW amounts produce significant flux. But the numerous hours with small SLW amounts also produce significant flux over the course of an entire winter.

2.2 Field Observations of SLW

Huggins (1995) presented seasonal average portrayals of the cross-barrier SLW distribution over the Plateau. That work and other articles herein demonstrate the expected formation of SLW by forced orographic uplift over the west (windward) slope of the Plateau. Embedded convection, usually weak, enhances SLW production during some storm phases, and maximum SLW amounts are found above the windward slope. The gravity wave mechanism can also enhance SLW production as discussed in section 5. Snowfall often begins to reduce SLW amounts by the time cloudy air reaches the Plateau top's west edge, and the reduction continues as air flows eastward across the top (Huggins 1995). Both snowfall and subsiding airflow during passage across the Plateau lead to substantial SLW reduction. The SLW is largely depleted by the Plateau top's east (downwind) edge, approximately 10 km from the west edge, as a result of both snowfall and subsidence of the cloudy air.

Sassen and Zhao (1993) used lidar, microwave radiometer, and other observations to investigate SLW over the Tushar Mountains, about 175 km southwest of the Plateau experimental area. They demonstrated that SLW was usually found at barrier levels in the 0 to -10 °C range. Sassen and Zhao (1993) concluded that SLW cloud thickness was often only 500 to 800 m, with some SLW clouds nearly 1,000 m thick. That finding, along with layer temperature observations, led to their important conclusion that there was only a limited "window" for AgI seeding success. This window involved the upper portions of relatively warm SLW clouds with base temperatures warmer than -7 °C. Clouds with tops colder than -12 °C appeared to efficiently convert SLW to ice particles. Silver iodide is not effective for ice particle formation for temperatures warmer than -6 °C even when high AgI concentrations are present. With the in-cloud AgI concentrations resulting from operational seeding, effective concentrations at prevailing temperatures are often too low for the seeding to produce significant snowfall.

Super (1994) discussed the implications of almost continuous observations during the early 1991 two-month field program. Measurements included SLW by microwave radiometer, gage precipitation, AgI by acoustical ice nucleus counter and supporting observations. Super (1994) concluded that the SLW flux over the Plateau top's windward edge well exceeded the average snowfall over the Plateau top, suggesting that seeding might have the potential to convert some of the "excess" flux to additional snowfall. Moreover, many of the wetter hours had no detectable snowfall. These findings indicated significant seeding potential *if a large fraction of the excess SLW flux could be* *converted to snowfall.*

To put microwave radiometer vertically-integrated hourly amounts of SLW into perspective, Super (1994) compared them with observed hourly snow water equivalents. Accumulations for all 179 h with at least 0.01 inch observed by one or more of the three Plateau top gages provided the median hourly accumulation value of 0.015 inch. Half the total snowfall fell during the 83 percent of the precipitating hours with hourly accumulations of 0.05 inch or less. These data illustrate that mountain snowfall usually occurs at light rates over numerous hours as has been shown at a number of Rocky Mountain locations. Super (1994) calculated the equivalent snowfall rate if all SLW flux was converted to snowfall which fell uniformly across the 10 km wide Plateau top with a typical cross-barrier wind speed of 10 m s^{-1}. He showed that a vertically-integrated hourly SLW amount in excess of 0.10 mm was needed to produce the median hourly snowfall accumulation of 0.015. Sixty-five percent of all hours with detectable SLW over the Plateau top's west edge had average SLW amounts less than 0.10 mm. A significant portion of the SLW will be naturally converted to snow. Therefore, it follows that even when AgI seeding is successful, typical hourly accumulations would be limited. Moreover, hours with SLW amounts less than about 0.05 mm have very limited potential for snowfall production by seeding.

Super (1995a) presented the results from all six early 1991 experiments during which valley-released AgI was detected at lowest aircraft sampling levels over the Plateau. Observations of SLW were presented from a Plateau top microwave radiometer and from aircraft sensors. Temperatures of SLW cloud reached by the AgI were usually only mildly supercooled, and estimated effective AgI ice nucleus concentrations were quite small. Aircraft measurements of ice particle concentrations and gage observations of snowfall indicated that any snowfall increases caused by seeding were at limited rates and occurred only when seeded clouds were colder than -9 °C at aircraft sampling altitudes.

2.3 Summary of SLW Findings

In summary, SLW not utilized in snowfall production often existed over the Plateau during at least portions of storm passages. During the early 1991 and early 1994 major field programs, SLW existed during pre-frontal southwest flow and typically disappeared after frontal passage, as soon as Plateau top winds shifted to northwest. The SLW was confined to a shallow layer less than 1000 m thick (often considerably less) above the Plateau where temperatures were typically mildly supercooled. For example, when vertically-integrated SLW amounts were significant (exceeding 0.07 mm), Plateau top temperatures were colder than -4 °C during less than 25 percent of the hours (Super 1994). The corresponding temperature 1000 m above the Plateau would be about -10 °C for in-cloud lapse rates. These temperature, SLW cloud thickness and percentage values illustrate that effective ground-based AgI seeding of the SLW layer is limited a fraction of the hours when significant SLW is present.

This general portrayal of SLW availability implies that effective seeding must create significant ice particle concentrations in the SLW cloud very soon after condensate is produced during transport of moist air up the Plateau's windward slope. Otherwise, growth times will be too limited for much snowfall production before the SLW is depleted. Accomplishment of ground-based seeding under these circumstances presents a significant challenge, especially with AgI, because the condensate is formed at only slightly supercooled temperatures. This challenge is not limited to the Plateau, as much of the Rocky Mountain region has similar shallow, slightly supercooled liquid water zones as reported by a number of authors.

3. TRANSPORT AND DISPERSION OF GROUND-RELEASED SEEDING AGENTS AND TRACER GAS

3.1 Background Information

Once the generalized distribution of SLW is known over a mountain barrier, it is of obvious interest to consider the transport and dispersion of seeding material to determine when, where, and in what concentrations the seeding material creates ice particles within the SLW cloud. Such transport and dispersion investigations were the second major research objective of the NOAA/Utah AMP.

The Utah operational seeding program has used

AgI for many years, and that seeding material was given priority in the Plateau experiments. Liquid propane seeding, which can create ice crystals at higher temperatures than AgI, was also given serious attention, since it was found that SLW was often too warm for AgI to be effective. Sulfur hexafluoride tracer gas was frequently used to simulate seeding material transport and dispersion because it can be detected in small concentrations by fast-response instruments.

Unless otherwise stated, AgI in this report refers to the aerosol produced by burning $AgI\text{-}NH_4I$-acetone-water solutions in seeding generators. This solution has been used in the Utah operational seeding program, and it was used during the experiments discussed herein, including use of high altitude generators. This aerosol is known to operate by the contact-freezing nucleation mechanism (DeMott et al. 1995), known to be a relatively slow process in typical orographic clouds that have limited cloud droplet concentrations, often between 50-200 droplets cm^{-3} (Rauber and Grant 1986).

3.2 Field Investigations of Transport and Dispersion

Super and Huggins (1992a, 1992b) considered the targeting of ground-released AgI during the early 1990 field program from three different approaches. Silver-in-snow analysis was done with bulk snow samples from 10 sampling sites within the operational seeding program's target area. There was little evidence that silver concentrations in snow from seeded periods were greater than from nonseeded periods. These results were similar to earlier findings from the Tushar Mountains, but quite different from some projects in other states where seeding clearly increased snow silver concentrations by about an order of magnitude (e.g., Super and Heimbach 1983).

Real-time ice nucleus sampling was conducted well up Big Cottonwood Canyon while AgI releases were made with two generators in and above the canyon mouth. The AgI was routinely observed at the surface sampling location, which was about 500 m higher in elevation than the highest AgI generator. However, estimated AgI concentrations were small at prevailing SLW cloud temperatures.

The third approach reported by Super and Huggins (1992b) used aircraft sampling of ground-released AgI and SF_6 during near-storm prefrontal conditions. Sampling was done during times when visual flight rules (VFR) operations were permissible, allowing sampling near the terrain. Four of the five aircraft missions of this type showed the AgI and tracer gas were confined to the boundary layer above the valley floor and were not transported over the Plateau. Plumes were found over the Plateau during part of the fifth mission, but estimated ice nucleus concentrations active at the observed cloud temperatures were quite limited.

Griffith et al. (1992) reported on instrument flight rules (IFR) aircraft sampling during the early 1991 program. Two case studies were selected for detailed discussion. Tracer gas released at the mouth of a major canyon was found over the Plateau during the two aircraft missions at temperatures near -12 to -17 °C, respectively. Ice particle concentrations, calculated from SF_6 measurements, were sufficient for seeding to have been effective. However, it is suspected that natural cloud processes were quite efficient during the unusually cold cloud temperatures of one (March 6, 1991) of the two missions, as very little SLW existed above the Plateau top's west edge or at aircraft levels. Moreover, Super (1995a) reported that the maximum snowfall accumulation for the three Plateau top gages was only 0.01 inch during the entire 3 h experiment. Therefore, even if seeding increased the snowfall from this cold, weak storm, any enhancement was at the trace level.

The Plateau top snowfall during the second mission of March 2, 1991, was also quite limited, even though all eight valley AgI generators had been operating for many hours, and AgI was abundant at relatively cold temperatures where SLW was plentiful. Super (1995a) reported two of the three Plateau top gages detected snowfall during the experiment, but only at trace levels, in spite of a noticeable increase in the aircraft observed ice particle concentration (IPC) within the AgI plume(s). This finding is not encouraging for the valley seeding mode of operation. Even though the March 2 mission was flown under conditions apparently ideal for seeding, and the valley-released AgI was transported to sufficiently cold SLW levels, any resulting snowfall was insignificant. It is speculated that AgI nucleation occurred too late for snowflake growth and fallout to occur on the Plateau.

Super (1994) examined SLW, snowfall, and AgI during 12 experimental days of the early 1991 season when valley seeding was being conducted. Using the then most current 1981 calibration of the NAWC generator Super (1994) concluded that the AgI concentrations measured on top the Plateau were insufficient for effective seeding unless the AgI reached SLW colder than about -12 °C. Even using the more optimistic AgI generator calibration reported by DeMott et al. (1995), estimated effective ice nucleus concentrations were too low as discussed by Super (1995a).

3.3 Analyses Based on Recent Laboratory Studies

A subset of the early 1991 data reported by Super (1994) has been reexamined for this paper using the latest calibration data for the NAWC AgI generator from DeMott et al. (1995). Values were used for "natural draft" conditions typical of light valley winds during seeding. An even 100 h from seven different relatively wet storm episodes met the following criteria: The eight valley AgI generators had been on for at least 2 h to allow for transport time, microwave radiometer SLW equaled or exceeded 0.05 mm above the Plateau top's west edge, and the co-located NCAR acoustical ice nucleus counter operated properly with its cloud chamber temperature near -20 °C.

The NCAR counter mean ice nucleus concentration (INC) observations for the 100 h were multiplied by 3.0 to bring them in line with the Colorado State University (CSU) calibration of this device based on the isothermal cloud chamber results, also at –20 °C. A correction was applied to the cloud chamber values to compensate for dilution airflow (DeMott et al. 1995). For the uncorrected values usually provided by CSU generator calibrations, the two NCAR counters tested were found to indicate about two-thirds of the INC observed in the Isothermal Cloud Chamber, and the two NCAR counters tested at CSU consistently agreed. A third NCAR counter, not tested at CSU, had also been used during the Plateau experiments. Periodic side-by-side comparisons showed consistent results among all three units in the field.

An adjusted INC exceeding 10 L^{-1} at -20 °C can be considered clear evidence of AgI presence because the natural background observed during many hours without seeding was rarely that great, usually being in the 0 to 5 L^{-1} (adjusted) range. Ninety percent of the 100 sampled hours meeting the stated criteria showed evidence of AgI, with the adjusted INC exceeding 10 L^{-1}. Half the hours exceeded 500 L^{-1}, effective at -20 °C, and 10 percent of the hours exceeded 2,000 L^{-1}. Therefore, the AgI was usually transported from the valley up to the canyon head, a vertical distance of over 900 m. This is remarkable when is it realized that valley-based inversions are common during winter storms. However, most hours with SLW amounts of 0.05 mm or greater had weak embedded convection present, which likely assisted vertical AgI transport.

As discussed by Super (1994, section 8.3) these 100 sampled hours may be atypical of most hours with SLW present because of the high frequency of embedded convection and associated large SLW amounts. Many additional hours were sampled, which have not been reported in the literature, during which very large AgI concentrations were confined to a shallow layer over the Sanpete Valley. A large fraction of these hours also had SLW present above the Plateau, although average amounts were less than the 100 h sample just discussed. During several experimental periods, the only AgI that could be found with an instrumented vehicle carrying an NCAR counter were within about 100 m elevation of the valley floor. During these experiments, when only background INC was found along the Plateau top, the vehicle was driven down a major canyon toward the town of Fairview in the valley. The INC effective at -20 °C would abruptly shift from background levels of 1-3 L^{-1} within the canyon to many thousands per liter as the vehicle passed below the canyon mouth just above Fairview. The NCAR counter would become saturated with ice crystals so absolute INC cannot be quantified beyond stating that they were at least thousands per liter. Clearly, as the eight valley generators were operated hour after hour, they produced vast quantities of AgI aerosol, trapped in a shallow layer above them. Valley winds during these events were no more than a light northward drift.

In spite of observations of trapped AgI during a number of experiments, it appears that the valley-released AgI was often transported to Plateau top altitudes when SLW was reasonably abundant as represented by the 100 h data set discussed above. However, it is necessary to consider the adjusted NCAR counter INC values in the context of typical Plateau top temperatures which are much warmer than the -20 °C cloud chamber operating temperature. For example, the median Plateau top temperature during all 100 h was a mild -2.6 °C, while the median for the 50 wettest hours, with SLW exceeding 0.16 mm, was an even warmer -1.5 °C. The latest calibration of the NAWC generator shows that the effective INC at -6 °C, the warmest temperature sampled in the CSU Isothermal Cloud Chamber, is only 1/4 of 1 percent of that at -20 °C. Hence, even an adjusted NCAR counter INC of 2,000 L^{-1} yields an estimated effective INC of 5 L^{-1}, considered too low for significant snowfall production (Super 1994, section 8.2). Furthermore, only 9 of the 100 h were colder than -6 °C at the Plateau top altitude of 2700 m.

A more recent data set by Holroyd and Super (1998) showed that the Plateau top temperature was colder than -7 °C during only 20 percent of AgI seeding experiments conducted during the 1994-95 and 1995-96 winters. Temperatures were even warmer during many other experiments when liquid propane seeding was attempted. These large data sets leave no doubt that SLW near the Plateau top is typically only slightly supercooled during storm episodes.

The CSU generator calibration showed that at -8°C the effective INC was 8 percent of that at -20 °C, while the effective INC increased to 33 percent at -10 °C. If the AgI concentrations measured on the Plateau existed at higher altitudes corresponding to these temperatures, the median effective INC would be 40 and 165 L^{-1}, respectively. Such concentrations would be considered sufficient for effective seeding. However, for typical in-cloud lapse rates, the stated temperatures would be about 800 and 1,100 m above the Plateau for the median Plateau top temperature of -2.6 °C.

Aircraft observations were made during six experimental days when valley-released AgI was transported to the lowest permissible aircraft sampling altitude, about 600 m about the average Plateau top terrain as reported by Super (1995a). Four of these experiments were conducted on some of the same days that provided the 100 h Plateau top data set just discussed. The aircraft missions showed that AgI concentrations 600 m above the Plateau were typically more than an order of magnitude less than those measured on top of the Plateau, both at the fixed canyon head site and by an instrumented vehicle driven along the Plateau top's west edge. Some of the lowest aircraft passes failed to detect any AgI during these experiments. On some other experimental days the aircraft failed to detect any AgI even though many passes were made while abundant AgI concentrations (at -20 °C) were being monitored on the Plateau. The considerable body of aircraft observations from many experimental days has shown that AgI is rarely transported as high as 1,000 m above the Plateau, and then only in weak concentrations.

Another important factor to be considered is the rate at which AgI activates ice particles. The discussion above presents the most optimistic case in which calculations of effective AgI concentrations assume total nucleation by the aerosol. However, CSU Isothermal Cloud Chamber AgI generator calibrations are done over extended periods, often tens of minutes, to allow aerosol the time necessary to nucleate. NCAR counters are operated at very high cloud droplet concentrations to enhance nucleation during their limited cloud chamber residence time. But Rocky Mountain orographic clouds have limited droplet concentrations (Rauber and Grant 1986).

DeMott et al. (1995) show that the AgI aerosol produced by the NAWC generator and the AgI-NH_4I-acetone-water solution operates by contact nucleation, a slow process. They calculated that, for a constant temperature, only about 7 percent of the potential yield would be realized during a 20 minute transit of this AgI aerosol through a natural cloud of 100 droplets cm^{-3}. Simple calculations of transport times within SLW cloud over the Plateau show that AgI will be exposed to liquid cloud on the order of 20 minutes. Therefore, prior calculations of INC effectiveness, based on NCAR counter measurements and the latest CSU generator calibration, are probably overestimated by more than an order of magnitude. The sooner ice particles are formed within SLW cloud, the greater their probability of growing to snowflake sizes and settling to the surface before being transported beyond the mountain barrier.

These INC observations indicate a limited window of opportunity for effective AgI seeding

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since measurements have shown little evidence of significant ice particle enhancement in cloud warmer than -9 °C. This finding is in agreement with the Tushar Mountains observations presented by Sassen and Zhao (1993). Both data sets demonstrate the difficulty of effective ground-based AgI seeding with mildly supercooled orographic clouds typical of Utah's mountains. Seedable opportunities are limited to the colder "tail" of the distribution of SLW temperatures.

Further evidence on this point was provided by the Bridger Range Experiment conducted in the colder climate of southwestern Montana. Statistical analysis of that experiment by Super and Heimbach (1983), later supported by aircraft microphysical observations (Super and Heimbach 1988), strongly suggested that AgI seeding from high altitude sites was effective only when ridge top (equivalent to Plateau top) temperatures were colder than -9 °C. About half the Bridger Range experimental periods were that cold. But if one assumes similar vertical transport of AgI over the Bridger Range and the Plateau, as aircraft observations have indicated, a much smaller fraction of Utah storm periods would be seedable with AgI. This comparison further indicates that effective ground-based AgI seeding in Utah is limited to a fraction of the time that SLW is available. Moreover, at least a portion of the apparent success of the Bridger Range seeding may have been due to the frequent in-cloud operation of the AgI generators, with instantaneous ice particle production caused by the supersaturated conditions very near the generators (Finnegan and Pitter 1988). It is known the AgI generators produce abundant quantities of water while consuming propane fuel and the acetone in which the AgI is mixed. This can lead to local condensation-freezing as soon as the AgI aerosol is exposed to the quite supersaturated and supercooled cloud. This rapid ice nucleation mechanism will not occur with valley-released AgI.

3.4 Seeding-Induced Snowfall Calculations

Laboratory observations have indicated that the NCAR counters used in the Plateau studies were in reasonable agreement with CSU Isothermal Cloud Chamber results. Plateau-top and aircraft observations of ice particle concentrations have been shown to be in reasonable agreement with NCAR counter estimates of effective ice nucleus concentrations using CSU generator calibrations to extrapolate to temperatures warmer than the -20 °C NCAR counter cloud chamber temperature. Therefore, it is reasonable to use CSU generator calibration data to calculate upper limit snowfall increases possible with the Utah operational seeding.

It will be assumed in the following calculations that seeding-induced ice crystals do not participate in any secondary "ice multiplication" process. That is, any single AgI aerosol particle will have the potential to produce only one ice crystal. There is ample justification for this assumption. The conditions necessary for significant ice particle multiplication to occur are reasonably well understood (Mossop 1985). Such conditions are not characteristic of Rocky Mountain orographic clouds, especially at the colder temperatures where AgI can be effective.

The latest CSU calibration of the NAWC generator, for the AgI solution used in Utah's operational seeding, can be used to show that it is highly unlikely that the Utah operational seeding program produced the snowfall increases suggested by previously cited statistical analyses. The normal April 1st snow water equivalent found at snow courses in or near the Plateau's experimental area is about 50 cm. The most recent statistical analysis by the seeding operator (Griffith et al. 1997) suggests that about a 15 percent seasonal increase was achieved, equivalent to 7.5 cm for a normal winter. Using the typical AgI generator spacing of 16 km (Griffith 1996) and approximate Plateau top width of 10 km provides an estimated area per generator of 1.6×10^{12} cm^2. The water volume provided by a 7.5 cm increase would be 1.2×10^{13} cm^3, equivalent to 1.2×10^{13} g of water mass.

We will make the highly optimistic assumption that *all the AgI aerosol reached SLW cloud at a relatively cold temperature of -8 °C*. This is contrary to the large NOAA/Utah AMP data set which indicates that only limited AgI reaches cloud temperatures that cold. The CSU calibration indicates the generator output at –8 °C is 1.4×10^{14} crystals g^{-1} for natural draft conditions. We will make the additional highly optimistic assumption that *all the available aerosol nucleated ice crystals at that temperature*. Then the resulting seasonal output of ice crystals can be calculated as 2.8×10^{17}, since generator output is 8 g h^{-1} (Griffith et al. 1992), and the generators are operated for about 250 h per 5 month winter (Super and Huggins 1992a, table 2). These crude and quite optimistic calculations yield an average mass per ice crystal of 0.04 mg per crystal. But as discussed by Super and Huggins (1992a) and Super (1994), observations from a number of locations show that the mass of a typical natural ice crystal is less than half that value. Furthermore, seeding-caused ice crystals are likely to be smaller because of less in-cloud residence time.

These calculated results would require that *all AgI reached a significantly colder temperature than supported by the multitude of field observations*. In reality, AgI was sometimes trapped in the upwind valley and did not reach SLW cloud. When it was transported over the Plateau, the bulk of the AgI was typically in a thin layer where temperatures were too warm for significant ice crystal formation. Often, this layer contained negligible SLW because natural snowfall processes consumed it. In-cloud residence times provided a further limitation to AgI nucleation ability. Finally, natural snowfall could be expected to sweep out some AgI aerosol. For all these reasons, the above calculations of the typical ice crystal mass which AgI would need to produce to achieve a 15 percent seasonal snowpack increase are excessively low. During the fraction of the time when storm conditions made it possible for seeding to create ice crystals, they would have to grow to unrealistically large sizes (masses) to produce the claimed 15 percent increase. *Therefore, such reported increases could not be the result of the Utah operational seeding program according to current physical understanding.*

Additional information on transport and dispersion is provided in the following two sections. It will be shown that release from high altitude locations, well up the windward slopes of the barrier, results in much more consistent transport over the Plateau. However, plume widths may be reduced as compared to valley releases. The vertical dispersion of the high altitude releases is not believed to be markedly different from valley releases. Both plume types were often found at, and limited to, the lowest aircraft sampling levels and below. Both plume types were sometimes too shallow for detection at even the lowest permissible aircraft sampling altitudes.

4. RESULTS OF PHYSICAL CLOUD SEEDING EXPERIMENTS

4.1 Background Information

There is no doubt that AgI released into sufficiently cold SLW cloud will produce multitudes of embryonic ice particles. The same result is achieved when liquid propane is expanded into even slightly supercooled liquid cloud. The challenge is to create seeding-induced ice particles at such locations that their subsequent trajectories will be within SLW cloud for a sufficient time (distance) to permit growth to precipitation sizes. The expectation is that some of the precipitation-sized ice particles will fall to the mountain surface as snow before sublimating in the lee subsidence zone. Ideally, the tiny seeding-caused crystals should be formed very soon after SLW condensate is produced as air is forced up a mountain barrier, is carried upward by embedded convection, is transported upward by gravity waves, or ascends by some combination thereof. Releasing AgI even at cloud base will not result in immediate nucleation unless the temperature is colder than -6 °C.

Numerous attempts were made to document the effectiveness of AgI and propane seeding in creating ice particles and snowfall during the Plateau experiments. Most emphasis was placed on such documentation during the limited programs of the 1994-95 and 1995-96 winters, as summarized by Super and Holroyd (1997) and Holroyd and Super (1998).

With two exceptions previously noted (March 2 and March 6, 1991) and discussed by Super (1995a), all AgI and propane seeding experiments which demonstrated IPC enhancements used high altitude release sites well up the windward slope of the Plateau. Unless specifically mentioned otherwise, it can be assumed that high altitude seeding sites were used in the cases to be discussed.

4.2 Case Study Analyses

The first article in this series to document seeding-caused ice particles was by Super and Holroyd (1994). A several-fold enhancement in IPC was shown at aircraft levels for the experiment of February 17, 1991. The co-located AgI and SF_6 were both detected with aircraft instruments. Measurement of SF_6 with a fast-response detector allowed for precise delineation of the seeded zones. Seeding-caused IPC was near 70 L^{-1} at cloud temperatures of -13.0 to -15.5 °C over the Plateau top's west edge.

Holroyd et al. (1995) presented a detailed analysis, with numerical modeling support, of the February 21, 1994, experiment. It was shown that high concentrations of ice particles were associated with measured and predicted plume locations sampled on the Plateau top with an instrumented 4-wheel drive vehicle, and above the Plateau with the NOAA aircraft. Ice particle concentrations and precipitation rates were enhanced by a factor of about 10 along the Plateau top's west edge highway, and by about a factor of 40 according to aircraft sampling above the west edge. Most growth was upwind of these sampling tracks, that is, above the windward slope where SLW was concentrated. Aggregation of high concentrations of ice particles appeared to be the primary snowfall mechanism. Plateau top observations suggested that only limited precipitation reached the surface, perhaps 0.5 mm accumulation over a few hours at some gages. But no gages were sited near the windward edge where most seeding-induced snow likely fell.

Super (1995b) presented detailed analyses that demonstrated an obvious increase in IPC and snowfall associated with the propane seeding experiment of March 5, 1995. Less obvious but still fairly convincing evidence of IPC and snowfall enhancement was presented from an experiment on March 11, 1995. Light natural snowfall "contaminated" the impacts of propane seeding during the latter experiment.

Super (1996) showed another obvious case of IPC and snowfall enhancement caused by AgI seeding during relatively cold Plateau top temperatures (-10.7 °C). This seeding, on December 15, 1994, produced about 1 mm additional snowfall on the Plateau top's west edge during the hour of seeding. The successful March 5, 1995, propane experiment at a Plateau top temperature of -4.5 °C was again reviewed, and it was shown that AgI seeding soon after the propane seeding was ineffective under similar conditions.

Significant documentation of seeding-caused IPC and snowfall resulted from the 1994-95 and 1995-96 winter field programs. This could be expected since these limited, economical experiments were designed for that purpose. Moreover, it was practical to conduct many such experiments with only limited ground equipment and two to three field technicians. The basic design was to release seeding material, AgI or propane, in a brief "pulse" of one-half hour or one hour duration. The release point (HAS on figure 1) was on a high, exposed ridge only 4.2 km horizontal distance and 315 m below the instrumented "target" site (TAR on figure 1) located at the head of a major canyon. Prevailing southwest winds funneled the seeded cloud up the canyon and past the target. Ice particle characteristics and snowfall rates could be examined before, during, and after plume passage of the target.

Some experiments provided obvious IPC enhancement, and sometimes snowfall augmentation, when examined on a case study basis. However, seeding effects were not obvious in most of the experiments. Some of the failures to clearly demonstrate IPC increases were caused by cloud temperatures too warm for seeding agent effectiveness, especially when AgI was used. Other failures were due to short-term natural variability of snowfall rates that often masked the signal produced by any seeding-caused ice particles. It is likely that many of the seeding experiments created tiny crystals that were swept out by larger natural snowflakes and, therefore, were undetectable by the experimental design. Furthermore, abundant natural snow may have consumed all available SLW, thereby starving the embryonic seeding-induced crystals. This series of experiments showed the difficulties of clearly demonstrating ice particle and snowfall production in the presence of even light natural snow. Orographic clouds are not steady-state, and natural snowfall rates often vary considerably over a few tens of minutes or less.

4.3 Statistical Analysis of Pulsed Seeding Experiments

When natural snowfall was none to very light and seeding potential existed, obvious effects of seeding could be demonstrated (Super and Holroyd 1997). But such conditions occur during a minority of the time that orographic cloud is present. However, statistical analysis provided an overview of *all similar experiments conducted* during the 1994-95 and 1995-96 winters (Holroyd and Super 1998). There were indications of AgI effectiveness in creating small ice particles when target (Plateau top) temperatures were colder than about -6 °C. However, the number of such cases was limited because less than 20 percent of all seeding experiments had target temperatures colder than -7 °C. Stronger evidence existed of propane-caused small ice particles, and even the difference between using one propane nozzle (1994-95 winter) and two nozzles (1995-96 winter) was evident. Snowfall increases caused by the seeding-caused crystals were limited, as might be expected from the limited distance (4.2 km) and travel time (median 17 min) between seeding release and the target. This distance was purposely limited to maximize successful targeting as the seeded cloud was funneled up a major canyon.

Perhaps the most important finding of these "pulse seeding" experiments was that propane seeding was effective in producing ice particles even with slightly supercooled cloud at the dispenser site (-0.4 to -3.4 °C). About 10 ice particles L^{-1} was typical at the target with one propane nozzle releasing about 3 gal h^{-1}, and 20 L^{-1} with two nozzles releasing twice that rate. As argued by Super (1994), a seeded IPC over a target in excess of 10 L^{-1} has the potential to produce meaningful snowfall. Holroyd and Super (1998) confirm that view as their figure 3 shows only a small fraction of the many hours with significant natural snowfall at the target had IPC less than 10 L^{-1}. The target IPC during natural snowfall was usually between 20 to 200 L^{-1}. Some operational programs have attempted to enhance snowfall with estimated IPC near 1 L^{-1}. Such an approach would have a negligible chance of success in Utah and probably elsewhere.

Cases with target temperatures colder than -4 °C were usually seeded with AgI, but no evidence of AgI ice particle production was evident with target temperatures warmer than about -6 °C. As noted, periods with SLW cloud infrequently have Plateau top temperatures colder than -6 °C, which seriously limits the window of opportunity for ground-based AgI seeding unless significant vertical dispersion occurs. These experiments did not sample above the target (Plateau top) elevation, but earlier work demonstrated vertical dispersion of AgI was limited.

5. NUMERICAL MODELING RESULTS

5.1 Background Information

Numerical modeling provided significant insight into the physical processes involved during winter orographic storms over the Plateau. The model used in these investigations was the sophisticated, three-dimensional, time dependent numerical model developed by Terry Clark and associates at NCAR.

Modeling results should be treated with caution until it is demonstrated that they are in reasonable agreement with observations. However, observations are limited in time and space and are impractical to make in some very important locations over mountains. Therefore, model results can fill in where observations do not exist, provided model results and observations are in good agreement where both exist.

The Clark model was applied to the Mogollon Rim of Arizona, as discussed by Bruintjes et al. (1995). They showed the model was quite successful in reproducing the dispersions of SF_6 tracer gas observed during 1987 experiments (Super et al. 1989). The importance of gravity wave dynamics in the transport and dispersion of seeding material was demonstrated by their work.

5.2 Model Applications to the Wasatch Plateau

Heimbach and Hall (1994) discuss the Clark model and its application to the Plateau. They compared model results with a well-observed case from the early 1991 field season which involved seeding with valley AgI generators. Reasonable agreement was found with AgI plume positioning. Considerable pooling of AgI occurred within the valley, but a shallow layer was eventually transported over the Plateau. The importance of gravity waves in seeding agent vertical transport was demonstrated in agreement with the results of Bruintjes et al. (1995). Gravity waves were also found to be influential in the production of liquid water and its subsequent downwind depletion in zones of subsidence. The horizontal and vertical position of the seeding release point was critical in determining whether the model-simulated seeding agent was transported over the Plateau for particular conditions.

Modeling results also suggested that seeding from the San Pitch Mountains, the next barrier west (upwind) of the Plateau, might provide broader plumes, earlier ice nucleation, and opportunity for greater vertical transport. These factors might increase seeding effectiveness if embryonic seeding-induced crystals that formed over the San Pitch Mountains were transported into the SLW condensate zone over the Plateau's west slope, where further growth and fallout could occur. A similar approach was apparently successful during the Bridger Range Experiment (Super and Heimbach 1983), although the valley between the barriers was narrower. The approach of seeding on the windward slopes of one barrier to affect another farther downwind should receive further consideration in view of limited growth times found over the Plateau (e.g., Huggins 1995).

Reasonable model agreement with observations was found in the case of a high altitude ground release of AgI reported by Holroyd et al. (1995). This experiment produced marked IPC enhancement on and above the Plateau top and apparently limited accumulations of snowfall. The heights to which model-simulated AgI plumes reached were in good agreement with aircraft measurements. The model's smoothed terrain failed to simulate some of the small-scale but important effects of major canyons which funnel the airflow. The model produced weak and shallow clouds that were driven orographically with little buoyant contribution. Gravity waves were shown to be important for transport over the Plateau and produced a secondary maximum of simulated AgI over the eastern portions of the Plateau.

Heimbach and Hall (1996) and Heimbach et al. (1997) modeled a well-observed case study during which AgI was released from three valley generators and tracer gas was released in a major canyon mouth. In spite of a surface inversion, the AgI was transported up and over the Plateau in a shallow layer, below minimum aircraft sampling levels. The model results suggest the initial vertical impetus for vertical transport was by the gravity wave mechanism. This was followed by orographic forcing in a more organized westerly flow. The model simulation predicted the observed confinement of the AgI to a shallow layer.

5.3 Modeling of Generalized Weather Classes

Valley AgI seeding was modeled for five generalized weather classes by Heimbach et al. (1998). A total of 46 rawinsonde observations from the early 1991 and early 1994 field programs were grouped into five classes according to temperature profiles. (Nineteen additional soundings did not fit within the five class criteria.) In general, the modeled results were in agreement with well observed case studies selected to represent each sounding class. Some of the important results from the modeling include:

a. A tendency frequently existed for a low-level northward drift of the valley-released AgI, parallel to rather than over the Plateau.

b. Poor targeting resulted from valley releases during the two most stable classes. Thirty-seven percent of the classified soundings were in these two classes.

c. The best targeting was with the most unstable class, which also had the coldest temperatures, thereby resulting in greater AgI effectiveness in ice particle production. Twenty-six percent of the classified soundings were in this class.

d. Warm temperatures over the Plateau frequently resulted in negligible AgI effectiveness even when transport over the barrier occurred.

e. Strong upward motion existed over the valley under some stability and wind conditions because of gravity wave transport. This mechanism can significantly aid the transport of valley-released AgI, but its presence, magnitude, and location vary markedly with time.

f. Mechanical forcing is important for AgI transport over the Plateau.

g. In some conditions, there can be a westward and north-westward drift of valley-released tracer in spite of organized westerly flow aloft.

5.4 Summary of Model Results

In summary, the Clark model results were in good agreement with field observations. Valley-released AgI was often trapped by surface-based inversions and usually drifted northward, parallel to the Plateau, rather than over it. Sometimes the drift was westward or north westward, contrary to flow aloft. Very large AgI concentrations were modeled (and observed) along the valley floor on several occasions after generators had been operated for several hours.

A gravity wave mechanism sometimes aided the vertical AgI transport even in the presence of inversions. The positioning of the gravity waves relative to the terrain and AgI generator locations was critical in determining whether vertical AgI transport occurred. Since gravity wave positioning varies with time, and AgI generators are at fixed locations, it can be argued that generators should be located at various distances west of the Plateau across the broad upwind valley. Heimbach and Hall (1994) modeled this latter approach.

During more unstable conditions, the valley-released AgI was consistently transported over the Plateau. The AgI plumes were consistently shallow over the Plateau top, often below lowest aircraft sampling levels about 600 m above average Plateau top elevations. Prevailing cloud temperatures within the shallow plumes were frequently too warm for effective ice nucleation by the AgI.

It has been demonstrated by model-simulations and observations that valley-released AgI is transported over the Plateau during only a minority of hours with storm conditions. When transport does occur, the AgI plumes are often too warm for much ice nucleation. These two factors are in agreement with previous documentation from the Tushar Mountains of southern Utah (e.g., Sassen and Zhao 1993). These findings suggest that valley AgI releases should be augmented or replaced with other treatment technologies (e.g., high-altitude AgI releases and propane seeding) in order to increase the efficiency of the Utah operational cloud seeding program.

6. MISCELLANEOUS ASSOCIATED WORK

A number of topics were explored during the Plateau program that do not fit under the above section headings. Consequently, these are included here.

6.1 Effect of Type II Statistical Errors on Experimental Duration

Heimbach and Super (1992, 1996) explored the important problem of encountering type II statistical errors in past randomized weather modification experiments. A type II error occurs when an experiment fails to detect an actual response to seeding, usually because the experimental unit population is too limited. Many experiments did not estimate the duration (population size) needed to achieve an acceptably low probability of encountering a type II error, say 10 percent. If an experiment failed to indicate a seeding effect upon completion (usually determined by the sponsor's patience and available resources), a type II error may have caused the "failure". The only valid conclusion from such an experiment is that it failed to demonstrate anything about seeding effectiveness. Unfortunately, the incorrect interpretation is often given, that is, that the seeding approach did not produce the desired effect.

When attempts were made to estimate the experimental duration needed to demonstrate real seeding effects, it was usually assumed that each treated unit would respond in the same manner. A considerable body of physical evidence shows this assumption to be improbable. The effectiveness of seeding can be expected to vary widely depending upon cloud and airflow conditions. Heimbach and Super (1992, 1996) investigated the more likely possibility that different experimental units (storms or days) have different responses to treatment. They demonstrated that this more realistic response leads to much longer experimental durations than if every treated unit responded uniformly. This important finding raises the question of whether many past seeding experiments interpreted as failures were simply too brief to demonstrate real seeding responses. Of course, if their physical design was flawed, they should have failed whatever their duration. But the point is that little can be gleaned about the seeding effectiveness of many past statistical experiments because of the uncertainty of whether they had type II errors. While Heimbach and Super (1996) made recommendations for possible improvements in future statistical experiments, their main recommendation was that such experiments be postponed until a much improved physical understanding emerges. An improved physical understanding was the main goal of the NOAA/Utah AMP work.

6.2 Runoff Increases Associated with Snowfall Enhancement

Super and McPartland (1993) reported on an investigation of likely runoff increases from an *assumed seasonal snowpack increase of 10 percent*. Cloud seeding programs are usually evaluated in term of seasonal percentage increases of snow water equivalent, but water users are interested in streamflow enhancement. Historical snow water equivalent and streamflow measurements were used from high elevation watersheds in the Upper Colorado River Basin. Drainages were selected for which streamflow measurements were not significantly affected by upstream diversions and were not regulated by upstream reservoirs. A simple linear regression analysis predicted seasonal streamflow increases between 6 and 21 percent. Ten percent or more additional runoff was estimated for most drainages for the assumed 10 percent snow water equivalent increase, an encouraging result. Reasons for differing responses were discussed which included variations in geology, vegetation, drainage slope, and aspect.

6.3 New Instruments and Observational Approaches

A number of new instruments and observational approaches were developed and deployed during the NOAA/Utah AMP. For example, the mobile microwave radiometer (Huggins 1992, 1995, 1996; Wetzel et al. 1996) provided a useful new way to map SLW over a mountain barrier. This approach is particularly important when it is recognized that safety concerns often prevent instrumented aircraft from flying low enough to monitor the orographic cloud SLW field in the region where most snow particles grow. It is also far less expensive to operate a radiometer than an aircraft. If it turns out that SLW detection is needed to initiate seeding, the radiometer is a more cost effective way to monitor SLW.

Truck-mounted NCAR counters and SF_6 detectors were used in tracking plumes up and over the Plateau. One truck carrying plume detection equipment also had a vane-mounted 2D-C laser probe on a mast above it. The vane kept the probe pointed into the resultant wind as the truck was driven along the Plateau top, while an anemometer controlled the 2D-C strobe rate. Tower-mounted 2D-C probes, also pointed into the wind by vanes, provided similar ice particle observations at fixed locations (Super and Holroyd 1997). Use of vane-mounted 2D-C probes provided a new and more accurate means of observing ice crystals caused by seeding. As it became available in the early 1990s, Global Positioning System (GPS) equipment was used to record truck and aircraft positions.

Super (1993) reported on testing of an automated, self-antifreeze-recharging, recording precipitation gage in a winter mountain environment. This gage, manufactured by Electronic Techniques, Inc. (ETI), was shown to be as accurate as the conventional Belfort Universal gage which requires manual service and chart reduction.

Two methods of estimating AgI ice nucleus concentrations effective at cloud temperatures sampled by aircraft were discussed by Super and Holroyd (1994). One method used tracer gas concentration measurements while the other was based on NCAR counter observations. Both methods were compared with the preferred, but often unavailable, approach of directly observing resulting ice particle concentrations with a laser probe. The methods were found to provide reasonable first approximations for the AgI aerosol and cloud conditions sampled by the study.

The tracking of AgI and SF_6 tracer gas with instruments on aircraft and ground vehicles was important in many of the reported studies. The sometimes maligned NCAR acoustical ice nucleus counter was shown to closely approximate AgI observations made by the "standard" CSU Cloud Simulation Laboratory (DeMott et al. 1995). Of course, the counter must be in good condition and must be maintained by someone knowledgeable in its proper operation. Several past applications used faulty NCAR counters or insufficiently trained counter operators. The three NCAR counters used during the Plateau experiments were often compared with one another and consistently found to be in good agreement.

Considerable effort was expended in calibrating and comparing fast response SF_6 detectors during the field programs. Known concentrations of the gas were injected into the detectors at frequent intervals. Like NCAR counters, these instruments also require significant maintenance and knowledgeable operators.

The CSU laboratory studies by DeMott et al. (1995) provided a new calibration of the NAWC AgI generator. It demonstrated that improvements had been made since the last calibration because warmer temperature ice particle yields were significantly enhanced. In addition to the generator calibration with the standard AgI-NH_4I-acetone-water solution used Utah operational seeding, one was done with a solution also containing sodium iodide and paradichlorobenzene. This latter solution was expected to produce ice nuclei that operated by the condensation-freezing mechanism. Laboratory tests showed that ice crystal production rates were much faster with the latter solution. The results imply that an order of magnitude increase in ice crystal formation could be obtained simply by switching seeding solutions. It is strongly recommended that such a change be made in the operational program.

Considerable development, testing, and improvement of liquid propane dispensers was accomplished during the Plateau program. These dispensers were used during many of the seeding experiments. Propane dispenser development was based on important earlier work by Reynolds (1991) in California. A totally automated propane seeding system was constructed (Super et al. 1995). An icing rate meter detected SLW at the main propane dispenser site, and that dispenser and two satellite dispensers were turned on and off as appropriate by programmed data loggers. All propane dispensers were on high elevation exposed ridges well upwind of the main barrier. This automated system remains in operation in the mountains east of Ephraim, Utah, and a similar dispenser was recently deployed to the Wind River Range of Wyoming (Roger Hansen, personal communication).

Cripps and Abbott (1997) developed a prototype icing rate meter for possible use with propane dispensers. Ideally, each dispenser would be activated by its own icing rate meter whenever SLW was detected at the dispenser. It was hoped that more economical units could be developed, using direct current electrical power from solar panels. While initial tests were promising, additional field tests and possible modifications would be required before the device could be considered operational.

7. SUMMARY AND RECOMMENDATIONS

7.1 Overview

Results of the final several years of the NOAA/Utah AMP program, conducted on central Utah's Wasatch Plateau from early 1990 through early 1996, are summarized in this paper. Considerable earlier work accomplished on the Tushar Mountains of southern Utah has been presented elsewhere.

The main goals of the NOAA/Utah AMP have been to investigate the effectiveness of the Utah winter operational (applied) cloud seeding program and to recommend ways to improve that program's effectiveness. Findings and recommendations have been reported to the NOAA AMP and to the Utah Division of Water Resources. The latter agency partially sponsored the operational program in cooperation with local water user groups. Operational program sponsors obviously have decision making authority concerning implementation of changes suggested in this paper and elsewhere.

Findings and recommendations have been provided in various levels of detail. An extended overview is given in this paper. The reader is referred to the original 29 articles and conference papers for complete discussions of the various investigations. Finally, for anyone interested in greater detail, various contractor reports and field operation plans exist which are not listed herein.

7.2 Key Physical Questions

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The NOAA/Utah AMP did not pursue statistical evaluations of the operational seeding program because of the many difficulties and uncertainties involved with such analyses as referred to in section 1. Rather, the NOAA/Utah AMP used physical observations and reasoning, including sophisticated numerical modeling, to investigate the key processes involved in winter orographic cloud seeding aimed at snowfall augmentation. As noted in section 1.2, the key physical questions involved in evaluation of such seeding can be briefly stated as follows:

1. When, where, and in what quantities does SLW exist within orographic clouds in excess of that naturally converted to mountain snowfall?

2. When, where, and in what quantities does the seeding agent affect the SLW cloud, converting portions of it to embryonic ice particles? In Utah, the operational seeding agent has been AgI produced by valley generators using the acetone-silver iodide-ammonium iodide solution.

3. When, where, and in what quantities do the seeding-induced ice crystals grow to snowflake sizes and fall to the mountain surfaces?

Most of the investigations reported during the NOAA/Utah AMP addressed one of more of the above questions.

7.3 Key Physical Findings

Brief answers to the above questions, based largely on the work reported herein, are now stated.

a. A considerable body of evidence from the Plateau investigations and some other work shows that significant SLW cloud exists over western mountains in excess of that naturally converted to snowfall. This "excess" SLW flux represents a large fraction of seasonal snowfall amounts. While the existence of excess SLW water cloud has been assumed for decades, and is necessary for operational seeding to have any potential, adequate documentation has been provided only during the past several years. Field deployment of microwave radiometers has been especially important in this documentation.

b. Orographic cloud SLW varies rapidly in time and space. Some of the greatest SLW amounts have been found during storms with strong synoptic support which are naturally very efficient snow producers during some phases but inefficient during others. Conversely, weaker localized storms typically produce lesser SLW amounts but these persist over many hours per winter. Both storm types are important in total seasonal SLW flux production.

c. Orographic cloud SLW is usually found over the windward slopes and crests and rapidly diminishes further downwind, even as cloudy air moves across the relatively flat Plateau top, about 10 km wide. The SLW is depleted by a combination of snowfall production and subsidence.

d. The SLW cloud is confined to a shallow layer above the Plateau. Most SLW condensate exists in the lower 500 m above the terrain and SLW amounts are usually negligible by 1,000 m above the terrain. Forced orographic uplift, weak embedded convection, and gravity waves all combine to produce the liquid condensate.

e. The SLW cloud found near the mountainous terrain is typically mildly supercooled over Utah's mountains. Frequently, the SLW cloud is too warm for significant ice nucleation with AgI, except perhaps in its upper portions. Often natural ice nucleation processes become efficient as cloud temperatures become cold enough for effective AgI nucleation. Consequently, the window of opportunity for effective AgI seeding is limited to a fraction of the periods with excess SLW. To restate this important point, *most SLW periods cannot be effectively seeded with the present type of operationally applied AgI, especially when it is released from the ground with resulting limited vertical dispersion.*

f. The frequency of successful transport of AgI plumes over the Plateau is directly related to generator elevation relative to the mountain barrier. Plumes released from high altitude sites within 300 to 500 m of the Plateau top were routinely transported over the barrier when winds had a cross-barrier component, necessary for significant SLW production. Similar results have been demonstrated at several other mountainous locations, including Montana, Colorado, and Arizona. High altitude release sites on the Plateau were usually just below or just above cloud base.

g. While experimental cases are limited, a definite impression developed over the course of the experiments that canyon mouth releases have a significantly greater probability of over-Plateau transport than valley releases.

h. Plumes released from the valley floor are less likely to be transported over mountain barriers than plumes released from higher elevation sites. A number of experimental periods showed that AgI was trapped near the valley floor for several hours. However, storm periods with relatively abundant SLW over the Plateau and embedded convection present usually also had valley AgI transport to the Plateau top. Nevertheless, effective ice nucleus concentrations from valley-released AgI were usually quite small at prevailing cloud temperatures.

i. On some occasions, the gravity wave mechanism transported valley-released AgI over the Plateau in spite of valley-based inversions. The timing and frequency of gravity waves, and the specific surface locations affected by them, are all uncertain, but this mechanism is sometimes important in vertical transport of the AgI aerosol.

j. High altitude AgI generators have at least three advantages over valley-released generators. First and very important is their ability to routinely target the intended cloud zones.

k. Second, concentrations of AgI released by high altitude generators are usually much higher as are resulting ice particle concentrations. This was repeatedly shown by observations along the Plateau top and above the Plateau. The results of model simulations were in agreement with these surface and aircraft observations. The main reasons for the higher concentrations are less horizontal dispersion (vertical dispersions were similar) and greater probability of transport over the Plateau. Of course, this result likely means significantly less crosswind spacing between high altitude generators compared with the typical 16 km or so spacing between Utah valley generators. But closer spacing of valley generators, perhaps about 4 to 5 km apart, has been recognized as desirable for plume overlap by the operational seeding firm (Griffith 1996).

l. The third advantage of high altitude generators is that they are usually located within cloud or just below cloud base. The AgI generators produce a large water by-product from combustion of propane and acetone. The resulting high supersaturation very near the generators allows for instantaneous activation by the condensation-freezing mechanism (Finnegan and Pitter 1988, DeMott et al. 1995). Thus, under favorable conditions, embryonic ice crystals may be formed immediately downwind of the generators, providing important additional time for growth to snowflake sizes. The condensation-freezing mechanism is unlikely to occur with valley-releases of AgI. If ice crystals are occasionally formed because valley fog is present, they cannot be expected to survive transport to orographic cloud altitudes.

m. A fourth possible advantage of high altitude AgI releases is reduced potential for photo-deactivation of ice nucleating ability. This may not be a significant factor since limited sunlight penetrates the usual cloud deck over valley generators during storms. Moreover, earlier concerns about photo-deactivation (Dennis 1980) may be unwarranted, at least for the type of AgI aerosol operationally used in Utah (Super et al. 1975).

n. Disadvantages of high altitude AgI generators include the practical difficulties of installing and maintaining them at remote locations, and limited horizontal plume dispersion. While aerosol from high altitude generators will routinely be transported over the mountain barrier, cross-wind spacing of such generators should not exceed perhaps 5 km if most of the SLW condensate zone is to be affected. However, it may be more important to routinely seed a portion of the SLW cloud with adequate INC than to sometimes seed more of it with weak AgI concentrations. Vertical dispersion from the high altitude generators appeared similar to that from the valley-based generators, but this impression may be partially based on the much greater INC found during aircraft sampling within high altitude released plumes. Valley-released plumes generally had weak INC at aircraft altitudes.

o. A seeding solution was tested in the CSU laboratory which produces an AgICl-0.125NaCl aerosol rather than the AgI aerosol used in the Utah operational program. The laboratory results showed that the former solution can nucleate ice crystals by the condensation-freezing mechanism rather than the contact-freezing nucleation mechanism resulting from the operational seeding (in the absence of supersaturation at the generators). *This fast-acting aerosol was shown to increase the number of effective ice nuclei by over an order of magnitude in the limited time available for transport through orographic SLW cloud.* It is strongly recommended that the operational seeding program use this improved solution. This is one of a number of actions which could increase effective ice nucleus concentrations over Utah's mountain barriers.

p. Numerous physical seeding experiments demonstrated that sufficiently great AgI concentrations exposed to sufficiently cold SLW cloud will produce abundant ice particles. Ice particle concentrations were similar to those expected, based on earlier laboratory results, tending to verify laboratory findings in actual orographic cloud. When obvious seeding-caused snowfall occurred, rates were light as is typical of natural snowfalls. The heaviest hourly accumulation observed during the seeding experiments was 1 mm liquid equivalent.

q. Propane releases at rates of 3-7 gal h^{-1} were clearly demonstrated as capable of producing 10 to 20 ice crystals per liter at the Plateau top target site even during slightly supercooled conditions. This approach offers a practical adjunct or alternative to AgI seeding during the mildly supercooled episodes typical of Utah winter orographic storms. Moreover, propane seeding was totally automated, using an icing rate meter to detect SLW cloud and a data logger to "decide" to release the liquid propane only during seedable conditions.

7.4 Summary of Findings and Recommendations

In summary, SLW, the necessary raw material needed for glaciogenic cloud seeding to be effective is frequently present in Utah's orographic clouds. Amounts of SLW are adequate to provide the potential for artificial nucleation by cloud seeding to enhance the mountain snowfall at higher elevations. However, numerous physically-based investigations reported herein indicate that the current operational seeding program likely converts very little of the available SLW to additional snowfall.

The main problem with the Utah operational seeding program is that observed effective AgI ice nucleus concentrations are too low for significant snowfall enhancement from the mildly supercooled clouds. Much of the time, the entire SLW layer is too warm for effective seeding with AgI, which begins to nucleate ice crystals near -6 °C, but which is ineffective in the concentrations observed until the SLW cloud is colder than about -9 °C. Under such circumstances, a different seeding agent is needed, such as liquid propane. When colder SLW cloud does exist, the window of opportunity is quite narrow before natural processes produce sufficient ice particles for effective snowfall.

A number of steps aimed at increasing the operational program's effectiveness can be taken. Admittedly, most of them would increase the program's cost. However, in terms of snow enhancement, these improvements may make economic sense. It is beyond the scope of this work to provide such economic evaluations.

If the Utah operational program continues to rely on AgI seeding, the following possible steps should be seriously considered for improving program effectiveness.

a. Convert to a seeding solution capable of producing an AgI aerosol which nucleates by the condensation-freezing mechanism rather than continuing to rely on slow-acting contact-freezing with the current solution.

b. Significantly increase the density of seeding generators and the ice nucleus output per generator. These steps will increase both effective ice nucleus concentrations and volume coverage within SLW clouds.

c. As a minimum, place AgI generators in canyon mouth rather than at valley floor locations. A superior approach would be to use high altitude generators located at least half way up the windward slope of mountain barriers.

d. Use high altitude generators on barriers immediately upwind of the intended target barriers, such as the San Pitch Mountains in the case of the Wasatch Plateau. This approach would provide important additional time for seeding-caused ice particles to grow and fall to the surface.

e. Seriously consider whether aircraft seeding can provide AgI aerosol to sufficiently cold SLW regions during relatively warm storm periods. The author recognizes that aircraft seeding with AgI generators will often be impractical when the SLW is contained in a shallow, mildly supercooled layer just above the mountain barrier. That is, aircraft with attached AgI generators will not be able to safely operate at sufficiently low altitudes during many storm episodes. Dropping of AgI flares is an alternative which is likely cost prohibitive when duration and volume of coverage are considered. While this author doubts that effective aircraft seeding would be practical and affordable, the question has not received serious consideration during the NOAA/Utah AMP. However, in light of the typical location and limited supercooling of liquid condensate over the Wasatch Plateau, aircraft seeding may deserve closer examination.

f. Whether or not AgI seeding is continued, it is recommended that automated liquid propane seeding be expanded from the three dispenser operation already in use east of Ephraim, Utah. This approach would profit from the use of direct current icing meters which could be operated in the field with solar panels and storage batteries. Available commercial models employ an alternating current heater requiring field use of an inverter. However, according to personal communication with one of their representatives, circuit changes could be made by the manufacturer. This approach should be affordable and has the several advantages previously discussed. Unlike automated AgI generators, automated propane dispensers are simple, reliable, and economical devices which can be programmed to release propane only when SLW exists at the dispensers.

g. Whatever the seeding approach, numerical modeling studies should be used to determine optimum seeding locations and source strengths of both AgI generators and liquid propane dispensers. The Clark model has been shown to produce reasonable simulations of the spatial distributions of SLW cloud and of tracer gas and small particle transport. The model is set up on a workstation and simulations can be produced at limited cost. The model should be run with various seeding configurations and under the range of storm conditions found in Utah. An abundance of sounding observations already exists for model initiation. Such modeling investigations should lead to improved AgI generator and propane dispenser placement. Reasonable estimates can be made of the AgI ice nucleus production and propane ice crystal production needed to affect the range of SLW cloud temperatures typically found over Utah's mountains.

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ORGANIZATION AND MAIN RESULTS OF THE HAIL SUPPRESSION PROGRAM IN THE NORTHERN AREA OF THE PROVINCE OF MENDOZA, ARGENTINA

Victor Makitov[1]
Scientific Director of Antigrad Latinoamericana

ABSTRACT

Cloud seeding activities for hail suppression using rockets are being carried out in the northern area of the Province of Mendoza, Argentina, from 1985 to 1998, with some interruptions. In the operational seasons 1993/94 to 1997/98, Antigrad Latinoamericana has conducted the Program. The target area reaches a surface of 200,000 hectares, of which 91,500 hectares are cultivated.

The technology is based in the seeding of the hail and potential hail clouds using a mixture of AgI as glaciogenic agent. The method is based in the hypothesis of the acceleration of the precipitation process or early rainout, which assumes the seeding of the area of formation of hail embryos in the periphery of the main updraft and in the area of feeder clouds, resulting in the "rainout" of smaller hydrometeors from less-mature, less vigorous clouds. The hydrometeors reach precipitation sizes prior to encountering the stronger updraughts capable of producing hail (WMP Report N° 26. WMO/TD-N° 764).

The evaluation of the effectiveness of the Program is carried out using the comparison of the historic data on damage by hail recorded in the target area in the period in which there were no activities of hail suppression. The average of hail damages to the crops during the 11 seasons with activities of hail suppression in the province of Mendoza was 4.22%, while in a period of 13 years without protection against the hail in the same area this same index was 12.45%.

1. INTRODUCTION

Cloud seeding to reduce hail damages is one of the technologies of higher interest in the present, as part of weather modification programs. As a result of the progress reached in the study of hail clouds during the last decade a transition in the work of hail suppression from the experimental to the operational field was seen in various countries. Hail suppression projects using rockets have had a wide diffusion in the 70's and 80's in the Soviet Union, China, Yugoslavia, Argentina, Brazil, Hungary and Bulgaria. Although change in the political and economic situation in the countries of Eastern Europe affected the development of the programs of cloud seeding, the total number of operational projects in these countries was 25 in 1992 (WMP Report N° 23. WMO/TD N° 686).

The improvement of the rocketry technique and the meteorological radars, the accumulation of experience in works carried out in different physical and geographical conditions as well as the application of the latest achievements in the theoretical and experimental conditions of hailstorm processes have determined the formulation of seeding technologies with very important methodological differences. Nowadays, it is almost impossible to talk about the "method of cloud seeding using rockets" without mentioning to which concrete project we are referring. This is due to the fact that not only the initial and finishing criteria of the seeding operations vary, but also the levels of temperature and the place of the introduction of the reagent, its concentration, etc. In other words, from one project to another the basic seeding methodology changes. It is precisely for this reason that the results obtained in some experimental programs (Federer et al., 1982) cannot be extended in a linear way to all programs of hail suppression which in the present time use the technology of seeding with rockets.

In our case, the seeding is carried out as function of the thermodynamic and aerosynoptic conditions which determine the type of hail formation processes, the data about their structure obtained by the radar, their dynamics of development, the

[1] Corresponding author address: Victor Makitov, Antigrad Latinoamericana S. A., San Martin, Mendoza, Republica Argentina
Phone/Fax: (54-2623) 42-7899, Email: antigrad@lanet.com.ar

categories of the hail and potentially hail cells.

Therefore, the objective of this article is to present a comparative analysis of the data on the seeded and non-seeded hail clouds, and also of the damages recorded during our experience in the Province of Mendoza, Republica Argentina.

2. ORGANIZATION OF THE HAIL SUPPRESSION PROGRAM IN MENDOZA

According to many of the indices of hail activity, such as the recurrence of the processes, their intensity, the number of hail cells, the duration of the almost stationary phase, the Province of Mendoza is one of the regions most affected by hail on the planet. Hail processes in the region are distinguished by their great diversity, their structure and dynamics of development, as well as by the synoptic and thermodynamic conditions of their formation. An intense heating of the surface, the irruption of the cold fronts, the penetration of tropical air from the north and northeast, together with the contrasting Antarctic cold fronts, coming from the south and southwest frequently favor the formation of unique synoptic situations, with a development of a strong convection of thunderstorms and hailstorms. In Mendoza, all the hail processes previously reported are observed, some of which have regional peculiarities that until now did not have a physical interpretation.

Hail suppression activities are being carried out from 1985 to 1998, with some interruptions. In the operational seasons 1993/94 to 1997/98, Antigrad Latinoamericana has conducted the Program. The annual period of an operational season is October 15 to the following April 15.

The applied method is based in the seeding of hail and potential hail clouds with a glaciogenic agent (a mixture of AgI) using three types of antihail rockets which are differentiated by the form in which the seeding material is dispersed, as well as in the trajectories of the flight and the effective seeding radios. The rockets Alazan-15 and Alazan-5 have an effective reach of 8 km and 11 km, respectively, and they disperse the seeding material from the tip. The rocket Crystal has an effective reach of 12 km and it disperses the reagent also from the tip, by means of 28 ejected cartridges, one at each 350 meters of flight.

The technology is based in the cloud seeding from 30 launching sites, which have 2 or 3 launchers with 12 rockets in each one. The launching sites are placed so that they can achieve the multiple cover of the target area and of a part of the surrounding territory, with special attention towards the preponderant directions of irruption of the hail processes. The target area is in the north of the Province of Mendoza and covers approximately 200,000 hectares, of which 91,500 hectares are cultivated with grape, stone fruits and, to a lesser extent, horticultural crops.

The Radar Center has two special meteorological radars MRL-5, of two different wavelengths (S band and X band). Both radars have been equipped with a computerized system of detection, processing and analysis of the information obtained by the radar, specially designed to operate over hailstorms. The system allows us to obtain in real time any type of horizontal and vertical sections of the radio echo, images of the upper and lower limits of the radio echo at any level of reflectivity of the radar, and maps of the total amount of precipitation and hail precipitation, which are expressed as projections of the levels of radar reflectivity and as isolines of kinetic energy of the precipitated hail. The seeded area is determined by the Project Manager in the computer screen, from which the software calculates the trajectories of the rockets necessary to completely cover the chosen area, selects the optimum launching sites, the type and number of rockets to be fired, and makes the necessary corrections of the firing coordinates as a function of the velocity and direction of the cloud displacement.

The Project Manager can adjust these determinations as a function of their own experience and capability. During seeding operations, the system controls the total consumption of rockets and the number of rockets available at each launching site. All the information obtained is recorded, forming a data file. At the Radar Center a local computer net is used; three of the computers receive information from the main radar and one of them from the reserve radar.

The computerized system has been improved on the basis of the experience obtained in our operational work in Mendoza. During the last season, various complements and adaptations were introduced to the system, such as the possibility of distinguishing any region of the radio echo, visualizing its parameters obtained by the radar in the screen; the possibility of displacing the seeding area outlined in the vertical section of the radio echo in any direction; the incorporation of a simulation program which recovers the file images in programmed intervals and the introduction of new algorithms which optimize the selection of launching sites when establishing the seeding areas.

The meteorological support includes data from radiosondes launched at the airport of the city of Mendoza, including the estimation of the height of the isotherm of 0°C carried out 8 times per day using a METSAT PC station; the acquisition of visible and infrared bands satellite images, as well as six types of synoptic maps, with the analysis and the weather forecasts for South America with an anticipation of up to 144 hours.

3. SEEDING HYPOTHESIS

Cloud seeding technologies currently used for hail suppression are mainly based on two physical principles: 1) beneficial competition and 2) acceleration in the formation of precipitation or early rainout. Their achievement assumes the simultaneous massive seeding of a specific surface, determining the place and the time of the seeding as a function of the thermodynamic state of the atmosphere, the information on the cloud structure obtained by the radar, and the state of development of the cloud. However, it is not always possible to rigorously establish which of the two hypothesis to use when carrying out a real seeding operation, as demonstrated when analyzing the characteristic trajectories for hailstones which grow naturally and for those which grow under the influence of the seeding (WMP Report N° 26. WMO/TD-N° 764).

The hypothesis of the early rainout, on which the technology used in Mendoza is based, assumes the seeding of the area of formation of hail embryos in the periphery of the main updraft and in the area of feeder clouds. These are the seeded areas in most of the hail suppression operational projects which use aircrafts as a way of delivering the glaciogenic agent (Rudolph et al., 1994; Smith et al., 1997). The seeding is designed to create a great number of artificial ice nuclei in this area to accelerate the natural growth of cloudy particles to reach the dimensions of precipitables particles. In these cases, the descent of the lower limit of the overhang of the radar echo and sometimes its total disappearance is ovserved. The regeneration of the hail cell is interrupted; the cloud acquires a more symmetric vertical structure, and the descent of the height of the increased reflectivity zone is detected, diminishing later the other radar parameters.

The hail and potential hail cells are divided into four categories as a function of the stage of the cloud development and the type of hailstorm, and the seeding of each cell is strictly made according to a specific method. As classification criteria, the values of parameters such as the maximum radar reflectivity of the radar echo Z max [DbZ], and the height of the different levels of reflectivity above the level of the isotherm of 0 °C (H_0)-dH_{25}, dH_{35}, dH_{45} [km], etc., are taken into account. The first radar echo generated at great height are part of the first category and are observed with particular attention when detected in the area of the main hail cell during the multicell hail processes. The clouds with potential hail warning and a tendency for rapid development are part of the second category. Hail and very strong hail clouds constitute the third and fourth categories, respectively (Reinking et al., 1994; Sanchez et al., 1998).

The seeding of cells of different categories is carried out as a function of the structure of the cloud observed by the radar, the kind of development of the process of hail formation in space, the size of the overhang of the radar echo and the velocity and direction of displacement of the radar echo. That's why the quantity of rockets necessary for the seeding vary in each particular case, being the average of rockets used per category the most demonstrative example. For instance, during the 1997/98 season, the average consumption of rockets was equal to 7.6, 19.3 and 66.8 for the categories II, III and IV, respectively.

4. COMPARATIVE ANALYSIS OF SEEDED AND NON-SEEDED HAIL CLOUDS

The questions related to the evaluation of the physical and economic effectiveness of any project of weather modification are based on specific hypothesis, since it is impossible to simply separate the natural evolution of the cloudy processes from their transformation as a result of seeding. At present, when carrying out the artificial stimulation of the precipitation, the most common practice is the realization of randomized experiments with posterior statistical evaluation of their effectiveness. It is evident that in the operational programs that protect a specific area, the possibility of any randomized seeding experiment is excluded. In this case, two traditional methods are used: the control area method and the historic series method.

The analysis of the results obtained in the 1996/97-1997/98 seasons, from this point of view, can be considered as a preliminary evaluation of the effectiveness of the work, while the posterior acquisition of experimental material on the seeded and non-seeded clouds and its statistical interpretation will allow this evaluation to acquire a greater base from the physical point of view.

An example of the development of hail clouds with and without seeding is presented where two hail clouds developed almost at the same time and under the same aerosynoptic conditions, one of which penetrates in the action area of launching sites and is seeded, while the other one moves by a parallel trajectory and goes near the target area and develops without any seeding.

In **Figure 1**, hail is expressed as isolines of kinetic energy of the precipitated hail. Cell 38, on January 20, 1998, developed north of the target area, outside the limits of the action area of launching sites. Cell 25, developed in the target area, was seed almost from the moment in which the first radar echo was detected. The estimation of kinetic energy was done by the computerized system, using the theoretical and semiempirical relationships (Z-E) (Waldvogel et al., 1978; Abshaev et al., 1985) and a special algorithm for the section of the rain region of the radar echo.

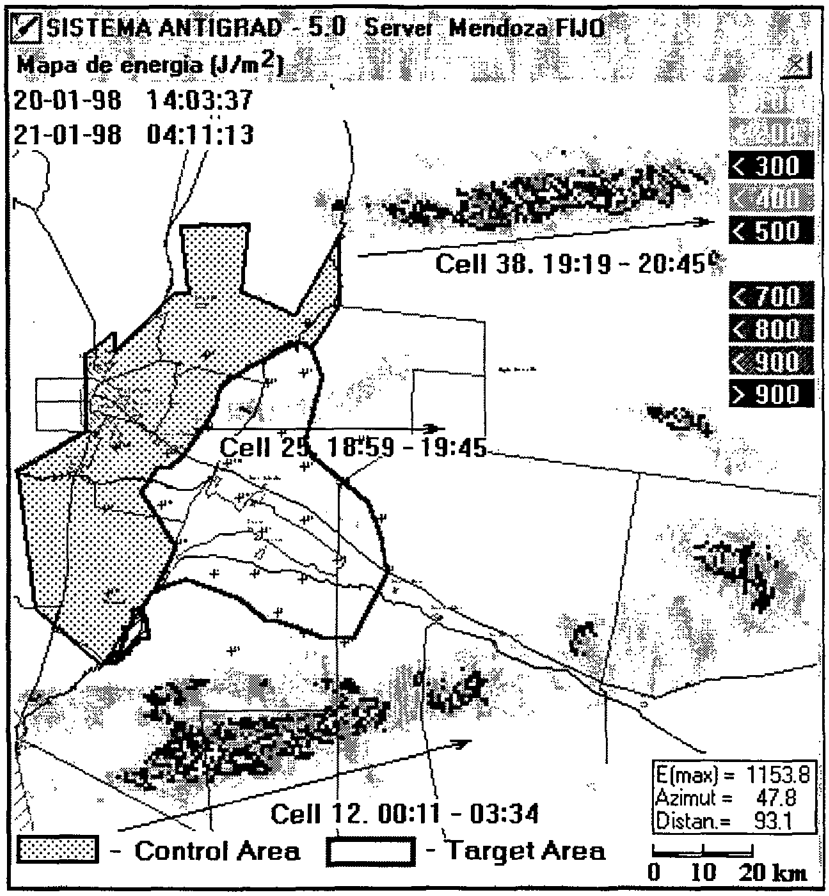

Figure 1

Fields of calculated kinetic energy of the precipitated hail on January 20, 1998, for the seeded (cell 25) and non-seeded (cells 12 and 38) hail clouds.

The cells were first detected 20 minutes apart. Cell 38 grew in natural conditions; in one and a half hours it covered a distance of more than 90 km, in 70 of which the fall of hail of great dimensions was noted. The maximum value of kinetic energy of the hail, measured by the radar, was of 1,153.8 J/m^2, which corresponds to a damage of 100% for any crop in any growing stage. 87 rockets (42 Alazan-15 and 45 Crystal) seeded cell 25, its duration was of 34 minutes, and the fall of hail of small size was observed in a reduced area, which did not produce any damages to the crops.

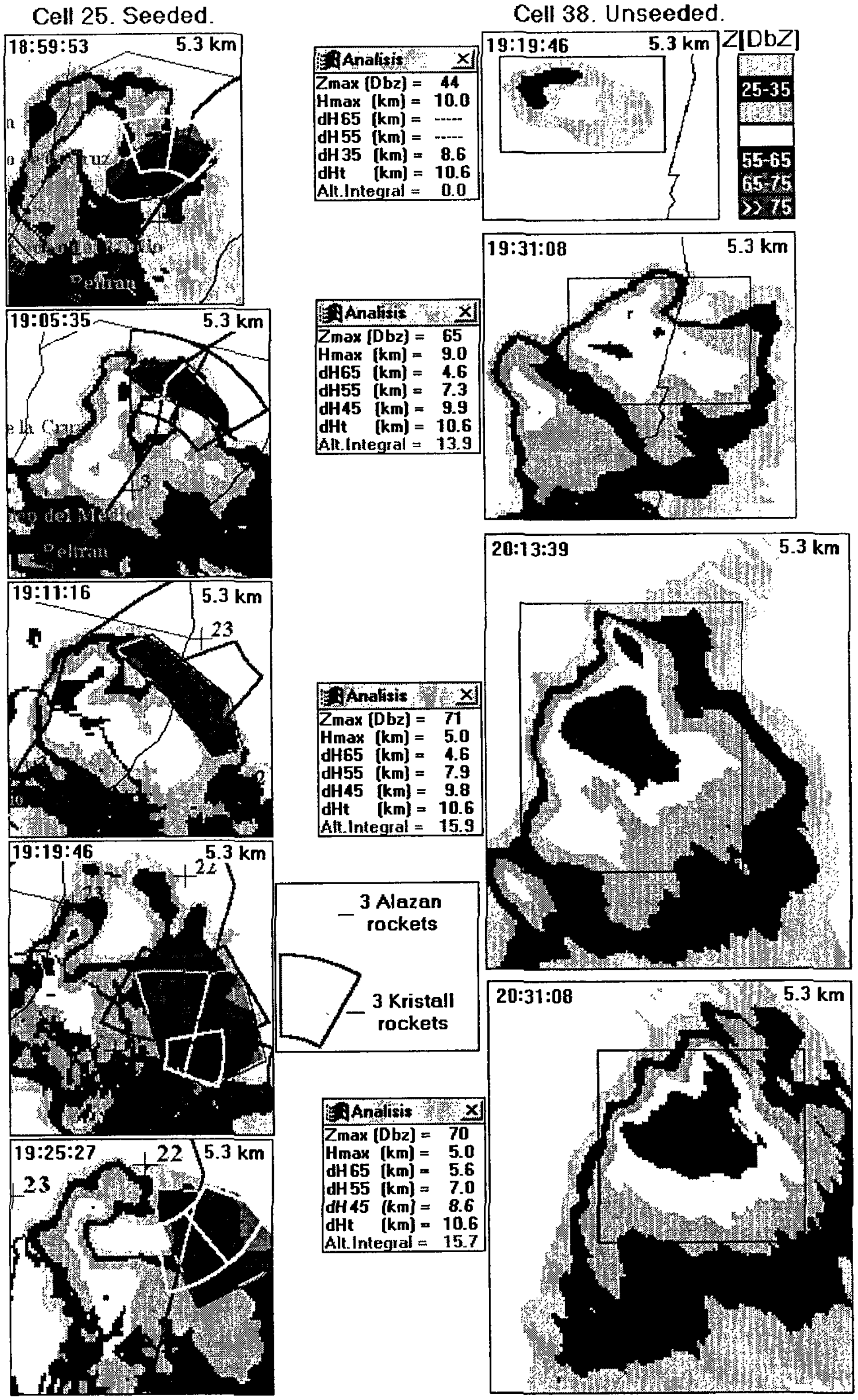

Figure 2

Evolution of the radar structure of hail cells 25 and 38. Presentation of the successive horizontal sections of the radar echo in the level of introduction of the seeding agent. The radar parameters of cell 38 correspond to the regions marked by straight angles.

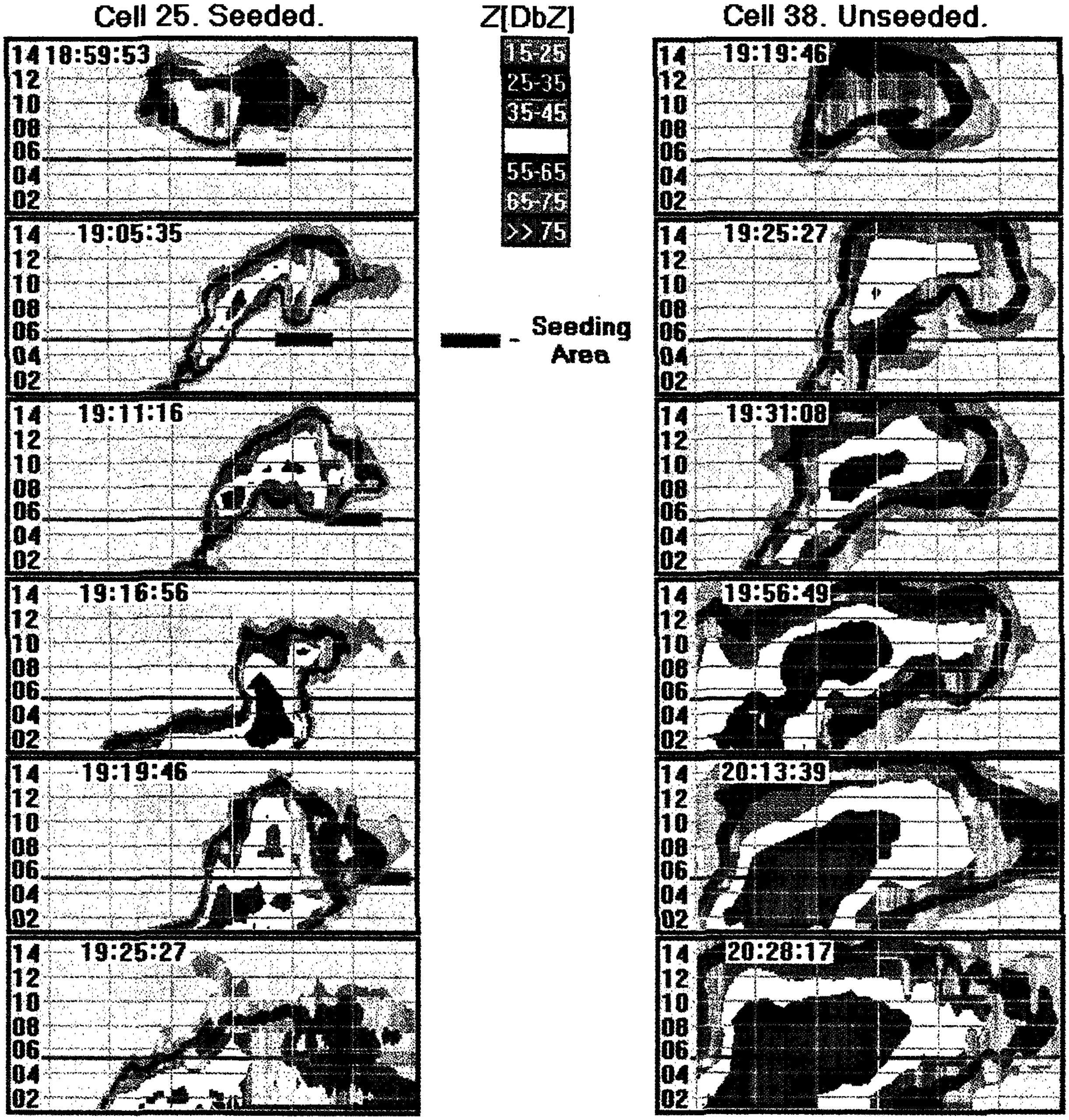

Figure 3
Vertical structure of the radar echo of hail cells 25 and 38 in a surface of maximum reflectivity of the radar.

The differences in the radar structure and in the growth dynamics of the cells are seen in **Figures 2** and **3**, where successive fragments of their vertical and horizontal sections are presented, as well as the trajectories of the introduced antihail rockets. It is interesting to notice that both cells have almost the same vertical structure of the first radio echo, recorded for cell 25 at 6:59 PM, and for cell 38 at 7:19 PM. However, the posterior development of cells differs remarkably. The development of cell 25 is subjected to a constant seeding of the frontal area of the overhang of the radar echo, at 7:11 PM its decrease is already observed, and near 7:19 PM its total precipitation and the interruption of the later cloud growth is observed.

The development of cell 38 proceeded more slowly, and just near 7:56 PM a strong nose of the radio echo of approximately 15 km in length is formed. The fragments of the vertical sections of this cell represent a classic example of a supercell hail cloud with in a stationary stage. In **Figure 4**, the temporal evolution of the main radar-derived parameters are shown.

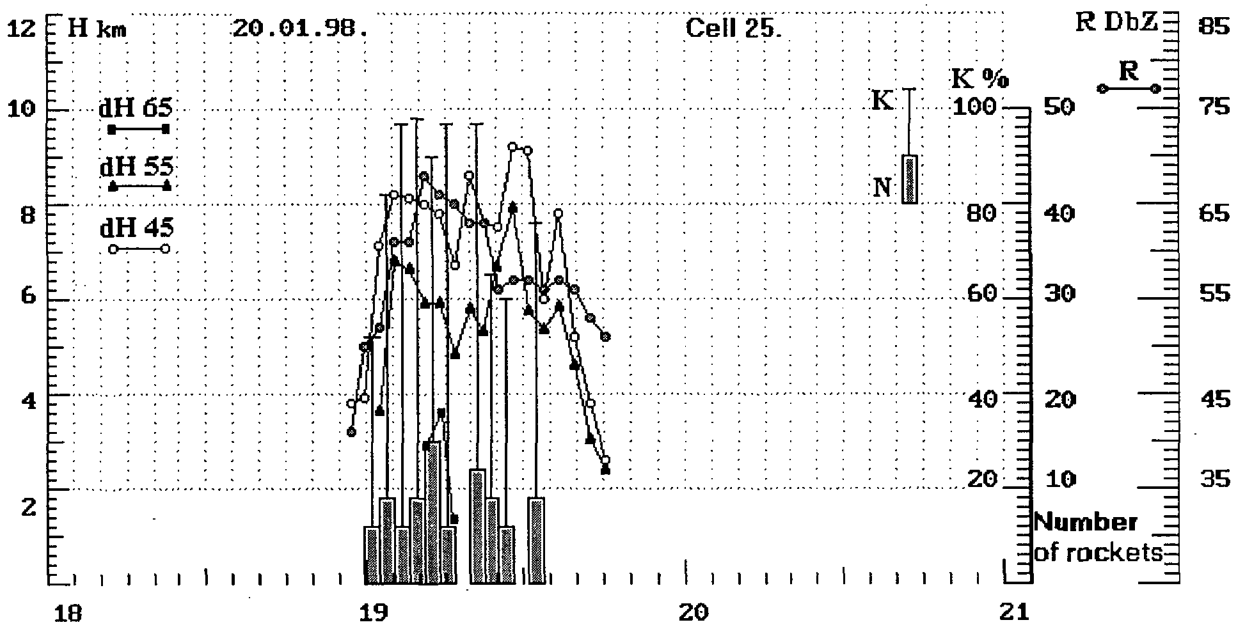

Figure 4

Temporal evolution of the main radar parameters of cell 25 on the bottom of the histogram of the introduced anti-hail rockets. The values dH_{65}, dH_{55} and dH_{45} correspond to the heights above the level of the isotherm of 0 °C of the regions of the radio echo, limited by contours with a radar reflectivity of 65, 55 and 45 DbZ, respectively.

It is evident that from this analysis conclusive evidence on the effectiveness of the method is not possible. However, through these examples, the general results of seeding operations in the study season are outlined.

5. ANALYSIS OF THE OPERATIONS' EFFECTIVENESS

Hail suppression activities are being carried out from 1985 to 1998, with some interruptions. In the operational seasons 1993/94 to 1997/98, Antigrad Latinoamericana has conducted the Program. The annual period of an operational season is October 15 to the following April 15. The temporarily interruption of the Program in the seasons 1992/93 and 1995/98 were due only to financial problems of the client.

The organization of the hail suppression program in Mendoza, outlined in the Section 2 of this paper, has been used just in the operational seasons 1996/97 and 1997/98. That's why we consider that the results obtained during such period, by using the computerized system, are most reliable, without mistakes due to subjective reading of the radar data by the operator.

The comparison of crop damages between the target and control areas shown in Figure 1, was done considering the similarity and coincidence of the climatological conditions, and the regularity on the repetition of hail processes, according to the radar data obtained since 1974 as well.

The only difference consists in the relationship between the total and the cultivated land on the above mentioned areas. The target area reaches a surface of 200.000 hectares, of which 91.500 hectares are cultivated, since in the control area the figures are of 220.000 and 50.000 hectares, respectively. Nevertheless, this is the only obtainable control area, considering that the defense is carried out in a local oasis.

5.1. Randomization:

In the 1997/98 season, a comparative analysis of hailstorms and of the damage caused by them in the target area before and during cloud seeding activities was carried out for the first time. In that season, hail suppression operations due to administrative reasons outside the project began on December 20, and not on October 15 as in anterior seasons. Hailstorms which developed in the target area before December 20 represented, in some manner, an independent selection of storms developed in a natural way which could be compared with a selection of seeded hail clouds. To compare the data about crop losses on the season 1997/98, before and after the initiation of the operations, it's necessary to consider that during January and the first half of February the maximum peak of damaging hail is registered, as well as the maximum repetition of hail processes.

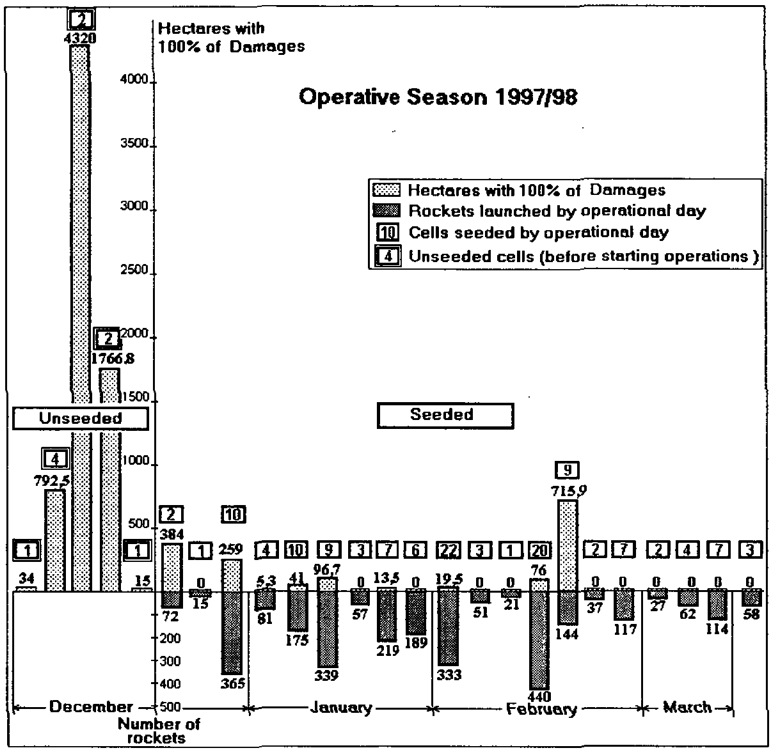

Figure 5

Distribution of hailstorms, damages estimated at 100%, and number of rockets fired in the season 1997/98

In **Figure 5**, the distribution of hailstorms with damaging hail, and rockets fired during the season are shown. In that figure, we can clearly observe that when there was a seeding, damages were significantly smaller. Moreover, all the storms developed over the target area prior to the beginning of the hail suppression operations caused damages, while in the 20 days with cloud seeding there were damages recorded in 9 cases and only in 3 of them they exceeded 100 hectares. Only 10 non-seeded hail cells before the beginning of the operations caused losses of 6,913.3 hectares, while 132 seeded hail cells damaged 1,626.9 hectares, calculated at 100% of damages. This comparison can be considered, in a cautious manner, as the results of an experiment of "forced" randomization, since all hailstorms, seeded or non-seeded, penetrated the target area in an autonomous way.

5.2. The control areas analysis:

The comparison of damages in the target area with damages in the control area corresponds with the analysis of the effectiveness of the work (Section 4).

It is difficult to choose an absolutely identical region for the control area, because the seeding is carried out in a local oasis, most of it surrounded by non-cultivated lands. The data on the damages in some cultivated areas, which were not part of the target area, could have some interest for the comparison. The area of comparison indicated in **Figure 1** is of approximately 220,000 hectares, but the percentage of cultivated lands here is considerably smaller than in the target area. In **Figure 6**, the distribution of damages produced by hail in the season 1996/97 in the target area and in the control area, as well as damages produced in the season 1997/98 before and during the defense are shown.

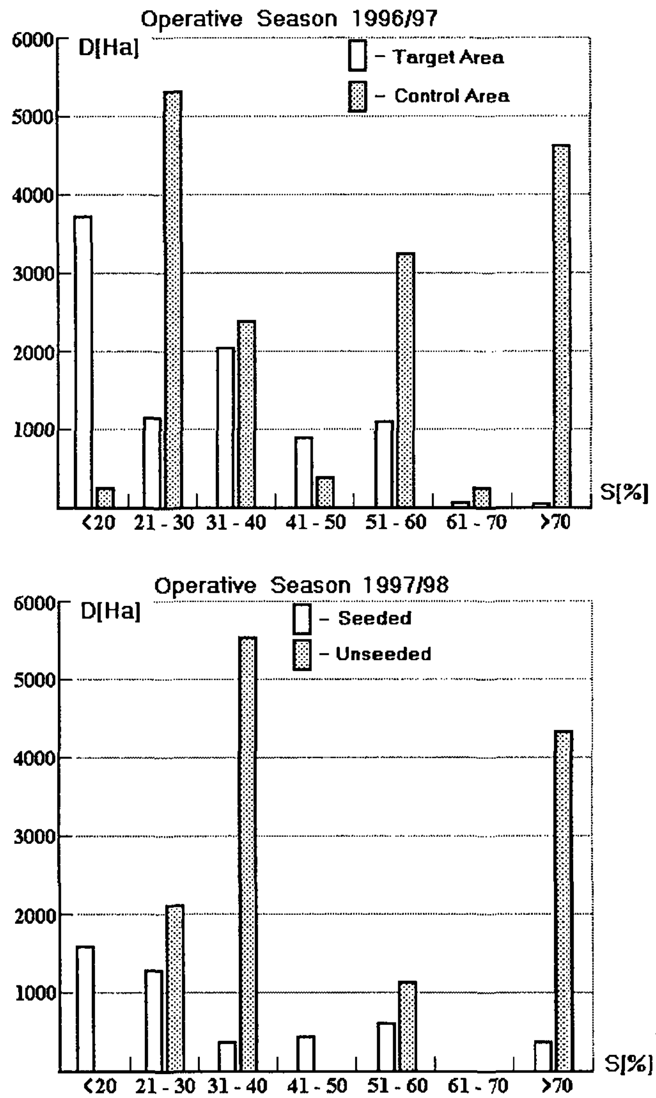

Figure 6

Distribution of percentage of damages for seeded and non-seeded hailstorms in the seasons 1996/97 and 1997/98

In the first season, hail damage in the target area, considered at 100%, reach to 2,653 hectares, while in the bordering area they reach to 8,342 hectares. An even more evident difference is seen in the areas with losses higher than 60 %. In the target area, the amount of hectares with damages exceeding 60% was of about 50 times less than in the control area, although the total surface of cultivated lands in the area under seeding is considerably greater than in the surrounding area.

In the second season, a great difference is observed when comparing areas with losses of 70 to 100%. Losses of these proportions reached in the period without seeding 4,329 hectares, while during the whole season of cloud seeding operations they reached 427 hectares, i.e., 10 times less. In other words, besides the reduction of total damages, in the target area we can see, as a result of the seeding operations, a redistribution of the areas with different percentages of damages, with a tendency towards a sudden decrease of the direct damages higher than 60%.

5.3. Historic series analysis:

A comparative analysis of the data recorded during many years in the current protected area on damage recorded in the period without hail suppression activities with the data obtained during hail suppression seasons gives a more precise idea on the decrease of the mean percentage of losses and the variation of its minimum and maximum values. The most reliable data that we have on hail damages recorded in the province of Mendoza without cloud seeding operations, have been obtained by the Provincial Institute of Agricultural Insurance, and correspond to a historic series of 13 years, from 1952 to 1965. Moreover, such data were obtained using the same criterion on evaluation of damages that are being used at the present.

No reliable data are available from the period 1965-1984. The period with action comprises 11 seasons of cloud seeding activities, from 1985/86 to 1997/98.

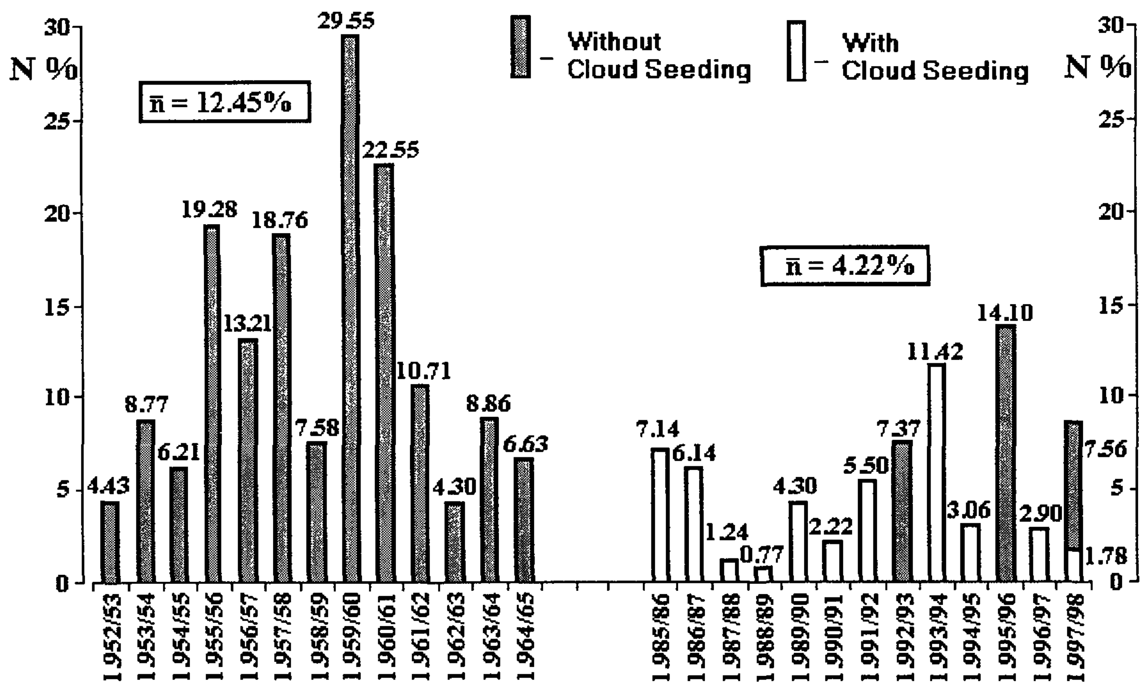

Figure 7

Distribution of the percentage of losses of the crops in the target area, without cloud seeding (1952/53-1964/65, according to official data from the Provincial Institute of Agricultural Insurance) and with cloud seeding (1985/86-1997/98, according to official data from the Ministry of Economics of Mendoza).

In **Figure** 7, the distribution of the relationship between the affected area, estimated at 100%, and the total of the cultivated area for the periods with and without seeding can be evaluated. As it can be seen in the figure, the mean percentage of losses decreased from 12.45% to 4.22%, the maximum from 29.55% to 11.42%, and the minimum from 4.30% to 0.77%. It is important to notice that the minimum percentage of losses of the crops without cloud seeding (4.30%) exceeds the mean percentage with cloud seeding (4.22%). It is natural that a more accurate comparison of these data could be possible with a greater number of seasons with cloud seeding in the considered area.

6. SUMMARY

The 1996/97 and 1997/98 seasons of hail suppression activities in Mendoza were characterized by a totally new organization of the work, the use of the computerized system of action, the local computing net, three types of antihail rockets and extended meteorological support. All these factors constitute the basis of the new project, which represents one of the last variants of the cloud seeding technology by using rockets. The great volume of experimental material obtained on the seeded and non-seeded clouds, as well as on the damages produced by them, requires a detailed physical and statistical analysis. This is necessary, 1) for the future improvement of the project and, 2) because it will allow us to judge with more reliability the possibilities of the method as a whole.

The preliminary results presented in this paper clearly demonstrate the differences in the evolution of the seeded and non-seeded hailstorms, the decrease of the total losses by hail in the target area in comparison with the control area, and the redistribution of the percentage of damages towards a sharp reduction in the areas with losses higher than 60%. As it is an operational program for the protection of a specific area, the future development of the methods of evaluation of the results of the seeding operations should obviously be based on data recorded by a terrestrial net of hail pads, placed in the target area, as well as in the cultivated and non-cultivated parts of the surrounding area. In this way, a more detailed and physically supported evaluation of the effectiveness of the seeding operations will be possible, taking into account the modification of the characteristics of the microstructure of the precipitated hail.

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COMPARISON OF RAINWATER SILVER CONCENTRATIONS FROM SEEDED AND NON-SEEDED DAYS IN LEON (SPAIN)

J. L. Sánchez[1], J. Dessens[2], J.L. Marcos[1], J.T. Fernández[1]

[1] Lab Física de la Atmósfera. Universidad de León. 24071 León.Spain
[2]Lab. d'Aérologie. UMR CNRS/UPS 5560 Université de Toulouse III

ABSTRACT: The long-term hail suppression projects arouse the public opinion's interest in the levels of pollution that may be reached in the precipitation. Even though the seeding material that is usually employed is AgI, and in spite of numerous references denying the toxicity of these emissions, it is easy to estimate the amount of AgI in rainwater, and the results obtained reassure the public opinion.
Within the hail suppression project corresponding to the acronym PALA (Plan for Hail Suppression Aims), which has been carried out in León (Spain) since 1986, there is a network of generators giving a total of nearly 200 grams of AgI per hour. 34 rain gages were employed to collect rainwater samples that have then been analyzed to determine the silver concentration. The average concentration on seeding days is 4.6 ppb, which is well below toxic concentration levels.

1. INTRODUCTION

Hail suppression activities are usually designed to be carried out over a period of many years, and the amount of AgI employed for seeding purposes may be significant. In areas where AgI has been released by ground generators for several years, it is advisable to measure the silver concentration present in the rainwater falling in that area.

Standler and Vonnegut (1972) and Howell (1977) raised a discussion about the possible effects of cloud seeding on human health in their articles, which are still prevailing. Several measurements carried out by other authors in various Weather Modification Projects were mentioned in these articles, and they all pointed out that the concentrations found were extremely low in comparison with toxic concentrations. More recent documents, like the one published by the WMO (1996) insist on the non-existent toxic impact of the Ag seeding procedures for Weather Modification purposes. There is a general consensus considering that silver concentrations in precipitation from storms seeded with silver iodide do not represent a risk factor for the environment, even in long-term projects (Klein, 1978; Potapov et al., 1996). On top of that it is necessary to consider that if a generator network has been "properly" installed, the concentrations of Ag in the rainwater fallen in the area surrounding the generators should be considerably higher on seeding days than on non-seeding days.

Therefore, the measurement of the Ag concentration in the rainwater helps in detecting whether the AgI emissions have reached the clouds chosen to be seeded. This does not mean, however, that Ag concentrations higher than the background concentration indicate that the AgI has "fulfilled" its function properly. Nevertheless, it can be considered as an additional factor contributing to evaluate whether the ground generator network for seeding aims was properly planned and carried out or not. So, there are references about measurements of Ag concentration in rainwater in the High Plans that indicate that the seeding agents had not been released in the proper locations in and around many "seeded" thunderstorms (Linkletter and Warburton, 1977, Warburton et al., 1982).

A network of automatic generators is being employed since 1986 for PALA (Plan for Hail Suppression Aims), a project that has been developed in León (Spain). The design of the network, especially the location and number of generators, was decided on the basis of the conclusions extracted from a previous climatological analysis (Sánchez et al., 1994).

In the years 1993 and 1994, the concentration of Ag in the rainwater was measured in 34 different places scattered over the target area, some on seeding days, some on non-seeding days. The aim was to establish whether the Ag concentration was significantly higher than the background concentration. This paper contains some results found.

2. EXPERIMENTAL DESIGN

The 10 generators are located as shown in figure 1. They have been installed covering an area of approximately 600 km2. Most of these generators are located outside the zone intended to be protected, because the network design was based on the goal of increasing the number of ice nuclei in the areas of storm formation. Therefore, the aim of the design was to install the generators mostly in those areas, even though in this case they are thus located outside the study zone. Once the storms have started, the winds (the prevailing winds are those with components of the third quadrant) often transport the AgI towards the target area. (Sánchez et al., 1994) The project design has the disadvantage that the winds do not always transport the seeding material into the storms that affect the target area.

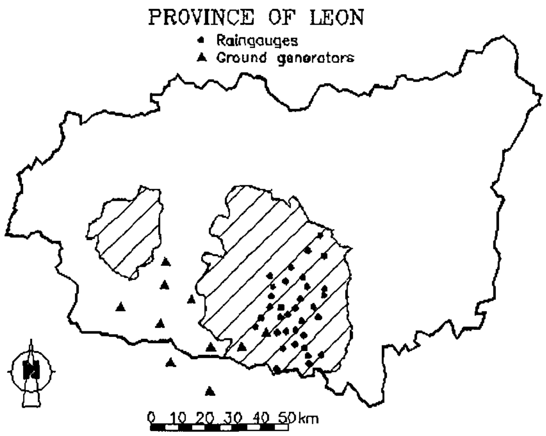

FIGURE 1: The triangles represent the location of each generator employed by PALA. The striped zone represents the protected area. The circles represent the location of the rain gage stations used to collect the samples.

It is important to take into account that this layout was not designed as an operative project. Its main objective is the improvement of our knowledge about the precipitation processes of thunderstorms, and about the changes that hail suppression activities may cause within these thunderstorms. It is thus necessary to gather data about seeding situations and non-seeding situations, to allow the comparison of databases. The layout helps establishing these two data series without too much social pressure on the part of the farmers for not being able to seed all the risk situations.

The use of the 10 generators forming a network installed in León leads to a total network emission of approximately 200 grams of AgI per hour, which means that 1,5 kg of AgI are given out on every seeding day.

Ag concentrations in rainwater superior to 50 ppm may have negative effects (U.S. Public Health Service). Thus, rainwater samples were taken in different parts of the target area. 34 rain gages were distributed to a number of volunteers, who situated them in different places within the target area to collect precipitation samples. Figure 1 shows the location of the 34 rain gages employed for taking rain samples. The different rain gauges are situated at a distance of between 5 and several tens of kilometers from the generators.

Every gage was inspected daily, and it was carefully cleaned and dried, to prevent pollution coming from the dry aerosol deposition that Ag compounds may contain. Once the precipitation had taken place (solid or liquid) it was poured into sterilized jars, and later put into a freezer. The volunteers stored the samples, and the PALA staff collected them regularly.

The samples were measured in a specialized laboratory of the Environmental Department of the Regional Authorities (Junta de Castilla y León). An atomic-absorption spectrometer was used, equipped with a graphite furnace. The samples were analyzed very carefully following the routines of the atomic absorption methods: drying for solvent evaporation, charring for matrix elimination, atomization for free atom formation and cleaning to remove the last traces of sample (Lacaux, 1972).

3. RESULTS AND DISCUSSION

Due to the fact that the land on which the generators were situated was rather mountainous, the plumes followed complex trajectories. Thus, it is important to be very cautious with any statement in this field. Nevertheless, if the precipitation caused by the most common storms in this territory is approximately of 10^4 or 10^5 m^3, with the network design established it would be unlikely that a storm could be seeded with more than 50 or 100 g of Ag. This means that the maximum Ag concentration that may be found in the rainwater should not exceed 0.5 or 1 ppm.

The analyzed samples correspond to those places where a precipitation of over 10ml was registered (corresponding to 2 mm precipitation). 10ml was the minimum established by the Laboratory of the Environmental Department for the sample to be analyzed with a guarantee of high accuracy.

Due to the fact that PALA employs a randomized seeding system, 147 valid samples were collected for analysis. 88 were obtained during seeding days and 59 during non-seeding days. These samples were taken on 34 different days.

The authors would like to point out that the stratification of the data has not taken into account other factors such as whether the plumes of the different generators approached the storms that precipitated over the target area or not. The main objective was to measure the Ag concentration found in the rainwater collected during those 34 days.

Finally, it is necessary to point out that in all cases the samples of rainwater collected were registered during the months of June, July and August, which are months during which the precipitation comes mainly from thunderstorms or hailstorms.

Table 1 shows the results found for seeding situations and non-seeding situations.

The Kruskall-Wallis test was applied to establish whether the samples belonged to the same distribution or to two different ones. The results show that for the significance level α=0.01 they belong to two different distributions.

Besides the results shown in table 1, the following points should be highlighted:

1. The average Ag concentration in rainwater on seeding days, taking into account all the rain gauges, is 3.2 times the concentration found on non-seeding days. The seeding material obviously leaves a trace in the rainwater. The layout of the generator network is thus consistent with the hypothesis that the seeding material appears in the precipitation collected in the protected area. There were 15 cases in which the Ag concentration found was below the minimum that can be detected (established in 0.1 ppb). The fact that 9 of these cases took place in seeding situations is not unexpected, for the layout of the generators does not guarantee that all the storms are actually seeded.
2. The maximum value found on seeding days - 157.7 ppb - is almost 9 times the maximum value found on non-seeding days. This finding might be expected. But what draws out attention is the fact that in both cases the samples were collected by rain gages located at a great distance from the western border of the area.
3. The Ag concentrations found in rainwater collected on non-seeding days are relatively high on average. This may be due to the fact that the atmosphere is not able to purify itself quickly from the AgI given out on seeding days. There is another possible explanation for this fact, namely the daily testing of the generators. All generators were working daily for approximately 15 - 20 minutes, even on non-seeding days, to test their correct performance. This small emission given out by the whole network (hardly 60 or 70 g of AgI) may leave a detectable trace in the rainwater.
4. Taking into account the fact that the Ag concentration required to be considered polluting should be around 50 ppm, we may conclude that not even in the worst of all cases have the concentrations reached these limits.

Variable	Seeded (ppb)	Unseeded (ppb)
Mean	14.8	4.6
Std	26.22	5.1
Max	157.7	18.4
Median	4.2	3.4
No. of times undetectable	9	6
No. of valid samples	88	59

Table 1: Statistical values for thunderstorms seeded and unseeded (see text)

CONCLUSIONS

With concentrations so far below the established limits any toxicity problem that could be attributed to the Ag emissions can be ruled out. Even if a person should drink the rainwater of the seeded storms without mixing it with any other water not containing this element, he or she would be completely safe. This result is similar to those found by Teller et al, (1976) in the San Juan Mountains (Colorado), Warburton (1973) in Alberta, Canada, and Super and Huggins (1992) in Utah.

And it reinforces the view that cloud seeding activities do not lead to toxic Ag concentrations in rainwater.

The Ag concentrations in the rainwater samples collected on seeding days strengthen the main idea of other research projects that have already been published. The Ag concentrations in the rainwater samples collected on seeding days follow a different distribution than the concentrations found on non-seeding days. This fact reinforces the idea that the AgI emissions are reaching the storms according to the hypothesis established in the project design. (Sanchez et al, 1994; Dessens et al, 1998).

ACKNOWLEDGEMENTS

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"REVIEWED"

EVALUATION OF THE WESTERN KANSAS WEATHER MODIFICATION PROGRAM

Darrel L. Eklund, Ph.D.
Daljit Singh Jawa, M.S., P.E.
Tina Kae Rajala, M.A.

Kansas Water Office
109 S.W. 9th St.
Topeka, KS 66612

Abstract - Weather modification activities began in Western Kansas in 1972 and several cloud seeding operations were conducted from 1972 through 1978. The centerpiece of weather modification activities in Kansas is represented by the Western Kansas Weather Modification Program that has operated from 1975 to the present time under the leadership of the Western Kansas Groundwater Management District No. 1. The primary objective of the Program has been to reduce hail damage, although a significant effort has also been made to increase precipitation. The Program has been evaluated on several previous occasions by various entities. However, the previous evaluation methodology and/or results have been viewed as somewhat inconclusive by the Kansas Water Office. The precipitation component as per the recent evaluation by the Kansas Water Office showed that precipitation declined by 0.25 inches in the target area from the pre-cloud seeding time period of 1941 to 1970 to the cloud seeding time period of 1979-1993. This amount of change in rainfall is well within normal precipitation variation and was determined to be of no practical economic significance. In contrast, the Kansas Water Office evaluation of the hail suppression component of the Program was very positive. The estimated percentage decrease in hail damage to crops in the target area was 27 percent, and resulted in an estimated benefit of approximately $60,000,000 to the six county target area for the 1979-1993 time period or $4,000,000 per year, after the expenses to operate the Program have been deducted. These figures are based on reduced hail damage to crops and do not include any estimate of the savings due to reduction in hail damage to dwellings, personal property, wildlife or other natural resources.

1. EVALUATION OF THE PRECIPITATION COMPONENT

1.1 Selection of an Operational Time Period

Two time periods were chosen for this evaluation effort. One time period was selected to represent a period of time during which the Western Kansas Weather Modification Program was operational. Although the Western Kansas Weather Modification Program began cloud seeding operations in 1975, the initial years of the operation from 1975-1978 were excluded from this analysis because cloud seeding operations were also being conducted within a 90-mile radius of Sherman County during 1975-1978. Hence, if this time period for analysis were to begin in 1975, it would be necessary to exclude Sherman County and several other Northwest Kansas counties from the control area discussed below. Therefore precipitation records were analyzed for the time period from 1979-1993, which represents a time period during which annual cloud seeding activities were taking place, in the target area counties, as a result of the Western Kansas Weather Modification Program and no such activities were occurring in the control area counties, listed below, or in any location that might have an impact on precipitation in the control counties.

1.2 Selection of a Historical Time Period

A historical time period from 1941-1970 was selected for comparison purposes, which represented a period of time during which no weather modification activities occurred in the vicinity of the control or target areas. Since cloud seeding operations occurred from 1972-1978 in portions of the control area, it was necessary to end the historical period in 1971 or before.

1.3 Study Areas

A target area and a control area were selected as study areas for precipitation analyses. The target area consisted of all counties that have fully participated in the Weather Modification Program each year from 1979-1993. These six counties were: Finney, Ford, Greeley, Haskell, Kearny and Lane.

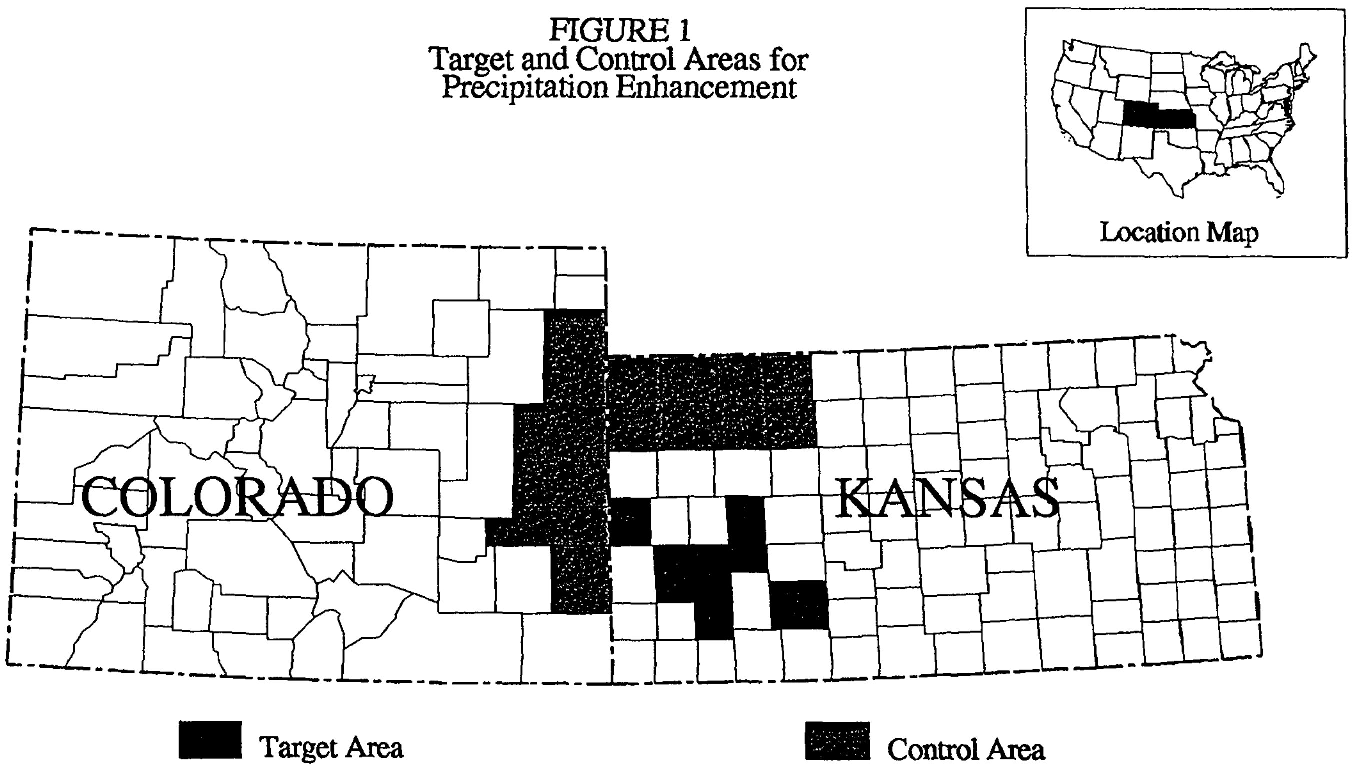
Figure 1 shows the target area in dark shading and the control area in light shading. No portion of the control area received any cloud seeding activity during either of the two time periods used for this study and it was not likely that any of the control area would have been impacted by any cloud seeding activities occurring outside of the control area or within the target area during either of the two time periods.

The northern portion of the control area consisted of Cheyenne, Rawlins, Decatur, Norton, Sherman, Thomas, Sheridan and Graham counties in Kansas. the control area did not include an eastern portion because the prevailing westerly winds cause a downwind effect of cloud seeding to the east of the target area. There was no southern portion of the control area because extensive cloud seeding operations in northwest Oklahoma and some in northwest Texas, preclude the selection of any control area counties that lie close to the southern portion of the target area. The western portion of the control area was located in Colorado and includes Yuma, Kit Carson, Cheyenne, Kiowa and Prower counties.

1.4 Seasonal Precipitation Data

U.S. Department of Commerce Climatological seasonal precipitation data were used for the months of May-August. These four months were active cloud seeding months for each year of the Weather

FIGURE 1
Target and Control Areas for Precipitation Enhancement



Modification Program during the 1979-1993 time period. Seasonal precipitation data were obtained for each year from 1941-1970, and from 1979-1993.

There were 28 precipitation stations within the 13 control area counties that were operational during most of the 1941-1970 and 1979-1993 time periods. There were 10 precipitation stations within the 6 target area counties that were operational during most of the 1941-1970 time period and 12 precipitation stations within the 6 target area counties that were operational during most of the 1979-1993 time period. Every county had at least one precipitation station throughout both time periods.

1.5 Analysis of Seasonal Precipitation Data

Step 1: Monthly precipitation data from multiple precipitation stations were averaged for each year by county, so that each county (control and target) had only one precipitation data value per month per year.

Step 2: An average seasonal precipitation value was calculated each year for the control area and for the target area.

Step 3: The control area average seasonal precipitation was calculated for the 1979-1993 time period by adding the 15 annual control area averages, calculated in Step 2, and dividing by 15.

Step 4: The control area average season precipitation for the 1941-1970 time period was calculated by adding the 30 annual control area averages, calculated in Step 2, and dividing by 30.

Step 5: The target area average seasonal precipitation was calculated for the 1941-1970 and the 1979-1993 time periods, as described in Steps 3 and 4 for the control area.

If the (1979-1993 target area average seasonal precipitation) minus the (1941-1970 historical target area average seasonal precipitation) exceeds the similar calculated value for the control area, by a significant amount, then it would appear likely that weather modification activities in the target area have had a positive effect on precipitation enhancement.

If T_1 = the 1979-1993 target area average seasonal precipitation, T_2 = the 1941-1970 historical target area average seasonal precipitation and C_1 and C_2 represent the corresponding control area averages, then the estimated change in the target area average seasonal precipitation due to weather modification activities, is calculated by:

$$Y = (T_1 - T_2) - (C_1 - C_2).$$

1.6 Precipitation Evaluation Results

The results of the analysis of precipitation data are presented in Table 1. It may be seen from Table 1 that the average seasonal precipitation for the target area was slightly less at 11.38 inches for the cloud seeding period from 1979-1993, in comparison to 11.63 inches for the pre-cloud seeding time period of 1941-1970. Hence, there was a decrease in precipitation of 0.25 inches. In contrast, the average seasonal precipitation for the control area was slightly higher at 12.00 inches for the cloud seeding period from 1979-1993, in comparison to 11.54 inches in the pre-cloud seeding time period of 1941-1970. The estimated change in the target area average seasonal precipitation, in inches, due to weather modification activities is determined from Table 1 as (11.38 - 11.63) - (12.00 - 11.54) = (-0.25) - (0.46) = -0.71 inches, which is very small in comparison to the annual variation in average seasonal precipitation, as may be seen from Figures 2 and 3.

Figure 2 shows the average seasonal precipitation by year and study area for the 1941-1970 time period. It is apparent from Figure 2 that the control and target area lines move pretty much in harmony, that is a wet year for the control area corresponds to a wet year for the target area and the same is true for dry years. A further review of the precipitation data shows that the control area average seasonal precipitation was higher than the target area average seasonal precipitation during 15 of the 30 years in the pre-seeding time period. Hence, there was a very close historical relationship in regard to seasonal precipitation for the two study areas.

Figure 3 shows the average seasonal

TABLE 1
AVERAGE SEASONAL PRECIPITATION BY TIME PERIOD AND STUDY AREA
KANSAS 1941-1970, 1979-1993

Study Area	Average Seasonal Precipitation By Time Period (Inches)		Difference (Inches)
	1979-1993	1941-1970	
Target	11.38	11.63	-0.25
Control	12.00	11.54	+0.46

FIGURE 2
Average Seasonal Precipitation by Year and Study Area, 1941-1970

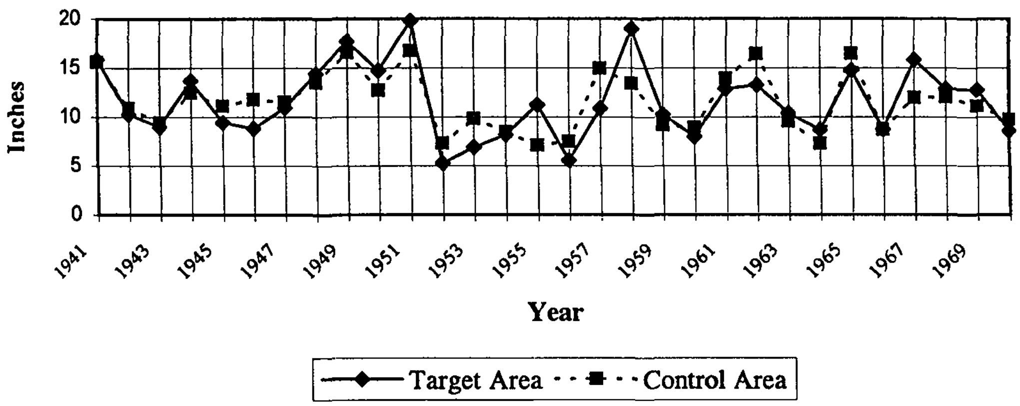
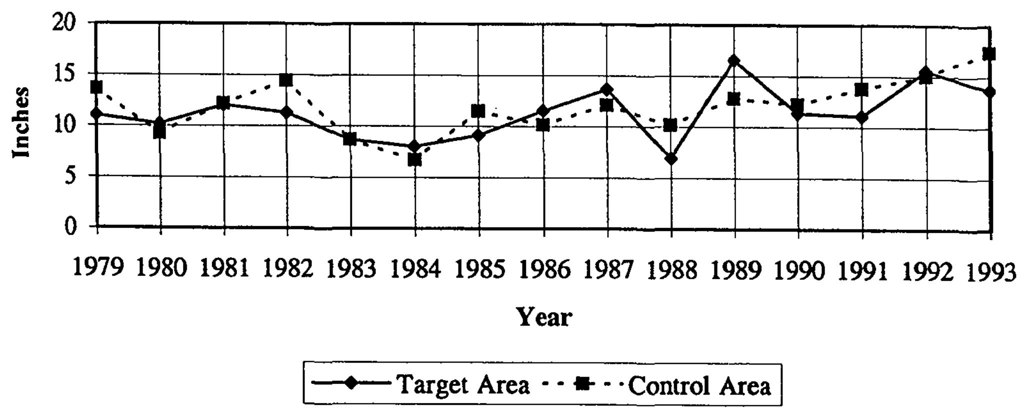


FIGURE 3
Average Seasonal Precipitation by Year and Study Area, 1979-1993



precipitation by year and study area for the 1979-1993 time period. As in Figure 2, it appears that the control and target area lines pretty much move in concert with one another. A closer examination of the precipitation data in Figure 3, shows that the control area average seasonal precipitation was higher than the target area average seasonal precipitation during eight of the 15 years in the cloud seeding time period.

These results provide strong evidence that there has been no change of practical significance in regard to the average seasonal precipitation between the control and target areas, as a result of the cloud seeding operations that have been carried out in Western Kansas.

It should be emphasized that there was tremendous natural variability in precipitation events. Weather stations were very widely scattered in the control and target areas and rainfall enhancement was not the primary focus of the Program during the 1979-1993 time period. Consequently it was not possible to place a high degree of reliability on the methodology used for this evaluation being able to detect any small impact that the Program had on precipitation in the target area.

1.7 Economic Significance

A linear regression analysis was run to determine if there was a statistically significant linear relationship between the average seasonal precipitation and annual crop values in the target area during the 1979-1993 time period. It was found that less than 10 percent of the variability in crop values could be explained by average seasonal precipitation, which was far from being a statistically significant relationship. Hence, it was concluded that the estimated decrease of -0.71 inches in the amount of average seasonal rainfall due to cloud seeding activities was of no practical economic significance. Apparently other factors, such as intensity of rainfall events, soil moisture level, timing of rainfall events with crop moisture needs, seasonal temperatures and crop prices may be much more important factors in determining crop value than simply the average seasonal precipitation.

2. EVALUATION OF THE HAIL SUPPRESSION COMPONENT

2.1 Selection of an Operational Time Period

Crop hail insurance records were analyzed for the time period from 1979-1993, which represents a time period during which annual cloud seeding activities were taking place as a result of the Western Kansas Weather Modification Program and no such activities were occurring in the control area counties, listed below, or in any location that might have an impact on hail suppression in the control counties.

2.2 Selection of a Historical Time Period

A historical time period from 1948-1970 was selected for comparison purposes, which represented a period of time during which no weather modification activities occurred in the vicinity of the control or target areas. The years from 1942-1947 were not included in this evaluation because the U.S. Bureau of Reclamation has indicated that hail loss records have improved considerably just after World War II in terms of both coverage and standardization.

2.3 Study Areas

A target area and a control area were selected as study areas for the hail suppression evaluation. The target area consisted of all counties that have fully participated in the Weather Modification Program each year from 1979-1993. These six counties were: Finney, Ford, Greeley, Haskell, Kearny and Lane.

Figure 4 shows the target area in dark shading and the control area in light shading. No portion of the control area received any cloud seeding activity during either of the two time periods used for this study and it was not likely that any of the control area would have been impacted by any cloud seeding activities occurring outside of the control area or within the target area during either of the two time periods. The control area lies entirely in Kansas and consists of Cheyenne, Rawlins, Decatur, Norton, Sherman, Thomas, Sheridan and Graham counties.

The control area did not include an eastern portion because the prevailing westerly winds cause a downwind effect of cloud seeding to the east of the target area. There was no southern portion of the control area because extensive cloud seeding operations in Northwest Oklahoma and some in Northwest Texas, precluded the selection of any control area counties that lie close to the southern portion of the target area. There was no western portion of the control area since the Kansas Water Office was unable to acquire crop hail insurance data for Colorado counties for each year of each of the two time periods.

2.4 Crop Hail Insurance Data

The National Crop Insurance Services in Overland Park, Kansas, was the source for crop hail insurance data.

Table 2 shows the minimum, average and maximum amount of crop hail liability insurance by study area, county and time period. In general, the amount of crop hail liability insurance sold may vary a considerable amount from year to year and is higher when crops are good.

FIGURE 4
Target and Control Areas for Hail Suppression

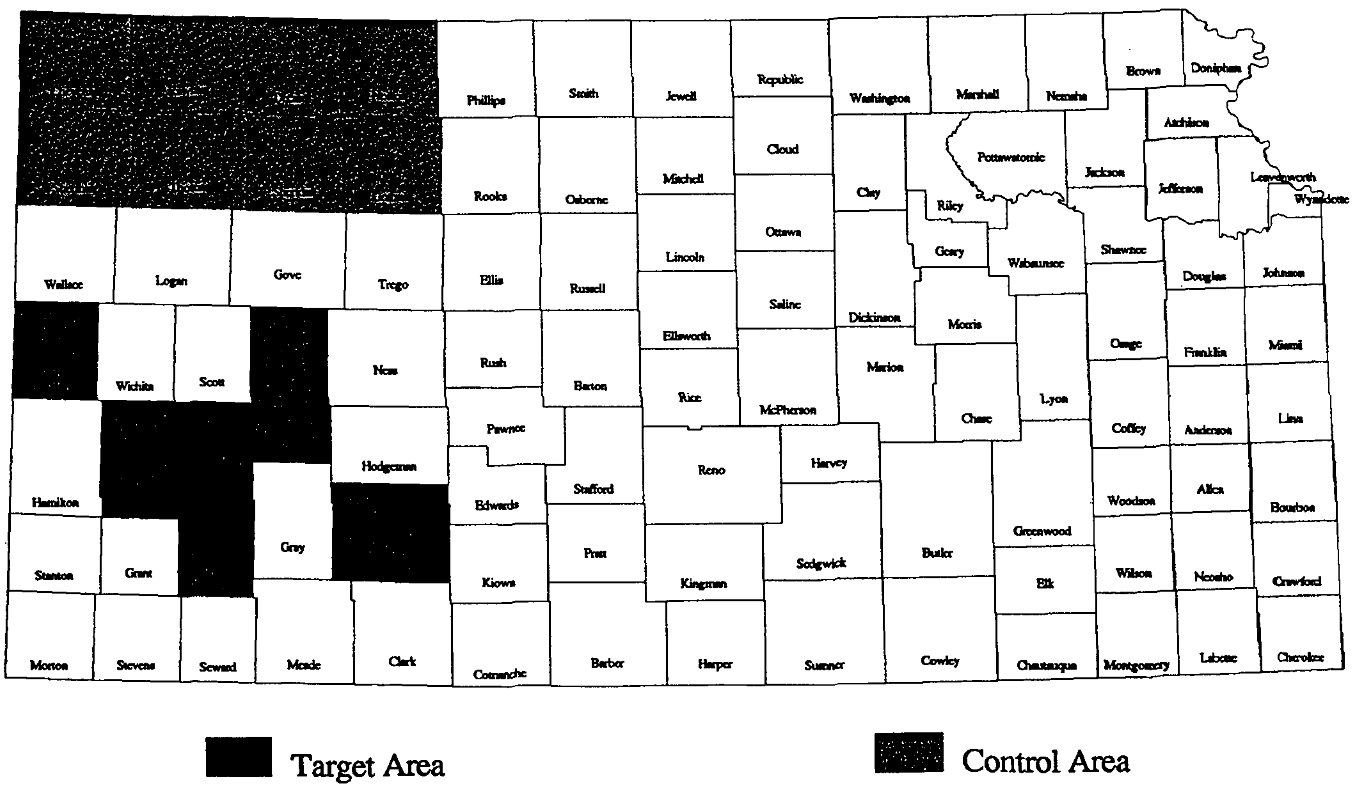


TABLE 2
MINIMUM, AVERAGE, AND MAXIMUM AMOUNT OF CROP HAIL LIABILITY INSURANCE BY STUDY AREA, COUNTY AND TIME PERIOD KANSAS, 1948-1970, 1979-1993

Study Area	County	Pre-Cloud Seeding Time Period 1948-1970			Cloud Seeding Time Period 1979-1993		
		Minimum	Average	Maximum	Minimum	Average	Maximum
Target	Finney	$172,662	$1,055,070	$1,854,398	$4,125,000	$9,122,667	$14,540,000
	Ford	$100,933	$681,244	$1,797,555	$4,861,000	$8,377,000	$17,978,000
	Greeley	$19,683	$420,041	$1,119,563	$235,000	$1,196,600	$2,940,000
	Haskell	$38,540	$819,295	$2,528,289	$11,756,000	$21,182,333	$30,563,000
	Kearny	$153,749	$448,581	$1,076,626	$1,417,000	$4,132,867	$8,371,000
	Lane	$121,085	$557,086	$1,272,967	$1,024,000	$2,289,867	$4,301,000
Control	Cheyenne	$289,645	$731,299	$1,392,399	$957,000	$1,470,067	$1,841,000
	Decatur	$377,220	$708,001	$1,266,614	$1,163,000	$2,671,400	$5,277,000
	Graham	$263,118	$514,736	$866,273	$1,015,000	$2,914,267	$5,233,000
	Norton	$383,533	$671,023	$1,008,131	$1,275,000	$2,574,933	$4,446,000
	Rawlins	$157,737	$578,722	$1,308,117	$684,000	$2,135,400	$3,923,000
	Sheridan	$375,692	$855,930	$1,558,570	$4,980,000	$9,427,933	$18,488,000
	Sherman	$72,185	$763,018	$1,838,125	$757,000	$2,133,533	$5,704,000
	Thomas	$206,325	$771,914	$1,550,113	$5,876,000	$7,317,733	$9,659,000

2.5 Analysis of Hail Suppression Data

The effectiveness of the cloud seeding operations in suppressing hail damage was measured by using a hail-damage loss cost analysis. Loss cost is a ratio found by dividing the insured crop hail-damage loss by the insured crop hail-damage liability and multiplying the result by 100.

Historical records show that hail-damage loss cost percentages decrease from west to east across Kansas. The double ratio analysis, used below, screens out differences between the target and control areas that may be due to regional differences in hail-damage intensity.

The following three equations were used to determine if the Western Kansas Weather

Modification Program has been effective in reducing hail damage in the target area.

$$R_1 = T_1 \div C_1 \text{, where} \quad (1)$$

T_1 = the average hail-damage loss cost ratio for the target area during the time period from 1979-1993, during which cloud seeding occurred in the target area and

C_1 = the average hail-damage loss cost ratio for the control area during the time period from 1979-1993.

$$R_2 = T_2 \div C_2 \text{, where} \quad (2)$$

T_2 = the average hail-damage loss cost ratio for the target area during the 1948-1970 time period, during which no cloud seeding occurred and

C_2 = the average hail-damage loss cost ratio for the control area during the 1948-1970 time period.

$$DR = R_1 \div R_2 \text{, where} \quad (3)$$

ratio R_1 reflects the results of cloud seeding on the target area hail-damage loss cost ratio for the 1979-1993 time period, as compared to no cloud seeding in the control area for the same time period. Ratio R_2 reflects differences in hail-damage loss cost ratios between the target and control area for the 1948-1970 time period, during which no cloud seeding occurred.

The following conclusions may result from this analysis:

1) $DR = 1$ This result would imply that the cloud seeding operations have had no effect on hail damage to crops in the target area.

2) $DR < 1$ This result would imply that the cloud seeding operations may have been effective in reducing crop-hail damage in the target area.

3) $DR > 1$ This result would imply that the cloud seeding operations may have caused an increase in crop-hail damage in the target area.

2.6 Hail Suppression Evaluation Results

The effectiveness of the cloud seeding operation in suppressing hail damage was measured by using a hail-damage loss cost ratio analysis, as described above where the loss cost ratio is defined below:

$$\text{Loss cost ratio} = \frac{\text{insured crop hail-damage loss}}{\text{insured crop hail-damage liability}} \times 100$$

The results of the analysis of crop hail data are presented in Table 3. For the cloud seeding time period of 1979-1993, the ratio $R_1 = (3.77 / 5.55) = 0.68$ is an indication that the magnitude of crop hail damage is less in the target area than in the control area, since the ratio is less than one. However, there was very little difference in the magnitude of crop hail damage between the target and control areas in the pre-seeding time period of 1948-1970, as the ratio $R_2 = (7.57 / 8.11) = 0.93$ is close to 1.00. The double ratio $DR = R_1 / R_2 = 0.68 / 0.93 = 0.73$ leads to the conclusion that the cloud seeding operations appear to have been effective in reducing crop-hail damage in the target area. The estimated percentage of reduction in crop-hail damage is $(1 - 0.73) \times 100 = 27$ percent for the 1979-1993 time period in the six county target area.

The loss cost ratios can also be illustrated graphically to show the differences between the two study areas and time periods. Figure 5 shows the average loss cost ratio by year and study area for 1948-1970, which was the pre-cloud seeding time period. During this 23 year time period, the target area had a higher loss cost ratio than the control area for 12 years or 52 percent of the time.

Figure 6 shows the average loss cost ratio by year and study area for 1979-1993, which was the cloud seeding time period. It appears from this graphical analysis that the cloud seeding has been beneficial for hail suppression, as the target area had a higher loss cost ratio than the control area for only four years or 27 percent of the time. It was also apparent that the annual difference in the loss cost ratios, between the target and control areas was much less during the cloud seeding time period.

TABLE 3
AVERAGE HAIL-DAMAGE LOSS COST RATIO BY TIME PERIOD AND STUDY AREA
KANSAS, 1948-1970, 1979-1993

Study Area	Average Hail-Damage Loss Cost Ratio By Time Period	
	1979-1993	1948-1970
Target	3.77 (T_1)	7.57 (T_2)
Control	5.55 (C_1)	8.11 (C_2)
Ratio	0.68 (R_1)	0.93 (R_2)

FIGURE 5
Average Loss Cost Ratio by Year and Study Area
1948-1970

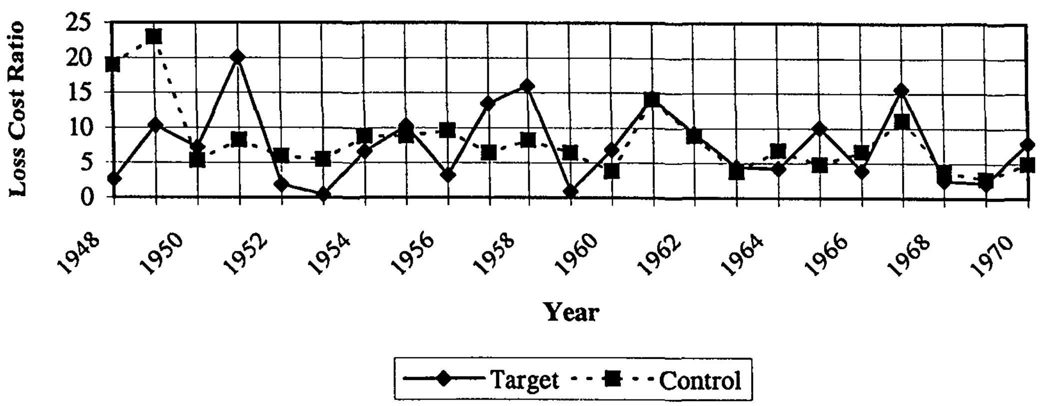
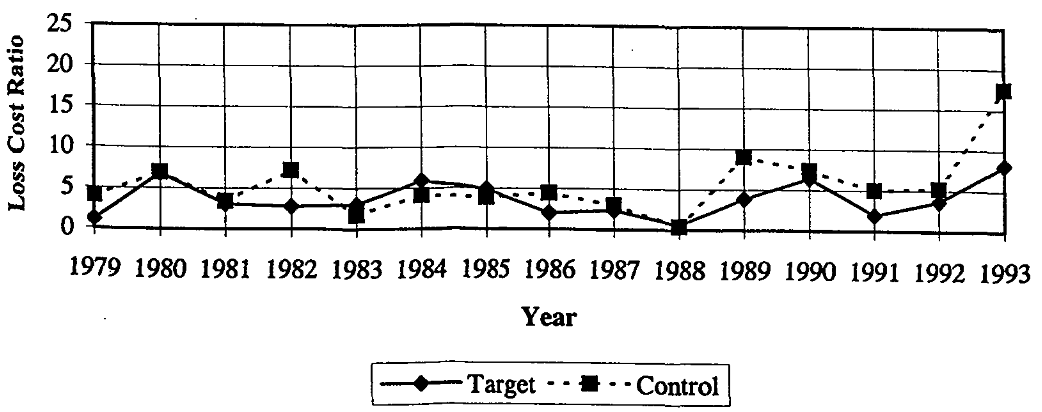


FIGURE 6
Average Loss Cost Ratio by Year and Study Area
1979-1993



2.7 Statistical Tests of Significance

A chi-square test of independence was conducted to test the null hypothesis that for the pre-cloud seeding time period (1948-1970) there was no relationship between the study areas (control and target) and the hail suppression loss cost ratio. The observed values for loss cost ratios for the pre-cloud seeding time period, were classified by size, as shown in Table 4 and represent county-year events. The 322 observations in the table represent the classification of annual loss cost ratios for each of the 14 study area counties and each of the 23 years in the 1948-1970 time period. The chi-square value was computed and found to be 0.16, which was not statistically significant and leads to acceptance of the null hypothesis that there is no relationship between the study areas (control and target) and the hail suppression loss cost ratio during the pre-cloud seeding time period.

A chi-square test of independence was also conducted to test the null hypothesis that for the cloud seeding time period (1979-1993) there was no relationship between the study areas (control and target) and the hail suppression loss cost ratio. The observed values for the cloud seeding time period are shown in Table 5 and represent county-year events. The 210 observations in the table represent the classification of annual loss cost ratios for each of the 14 study area counties and each of the 15 years in the 1979-1993 time period. The chi-square value was computed and found to be 5.38, which was statistically significant ($P<0.05$) and leads to rejection of the null hypothesis. Hence, a statistically significant relationship does exist between the study areas and the loss cost ratios during the cloud seeding time period. This statistical test showed that the Western Kansas Weather Modification Program has been effective in suppressing crop hail damage in the target area.

Table 4
COMPARISON OF LOSS COST RATIO AND STUDY AREAS
PRE-CLOUD SEEDING TIME PERIOD, KANSAS 1948 - 1970

Study Area	Loss Cost Ratio		Row Total
	Less than 10	10 or more	
Target	101	37	138
Control	131	53	184
Column Total	232	90	322

Table 5
COMPARISON OF LOSS COST RATIO AND STUDY AREAS
CLOUD SEEDING TIME PERIOD, KANSAS 1979 - 1993

Study Area	Loss Cost Ratio		Row Total
	Less than 10	10 or More	
Target	84	6	90
Control	99	21	120
Column Total	183	27	210

2.8 Economic Significance

A determination of practical economic significance was calculated below and was based on the results of the double ratio analysis shown above and utilized the crop values published in the Kansas Board of Agriculture's FARM FACTS publication series.

Step 1: A = the total 1979-1993 crop value in the six county target area
= $4,196,675,514

Step 2: B = the estimated total 1979-1993 crop value in the six county target area if no crop-hail damage had occurred.
= $A/(1-T_1/100)$
= ($4,196,675,514)/(1-3.77/100)
= $4,361,088,552

Step 3: C = the estimated total 1979-1993 crop-hail damage in the six county target area.
= B - A
= $4,361,088,552 - $4,196,675,514
= $164,413,038

Step 4: D = the estimated proportion of decrease in crop-hail damage in the six county target area during 1979-1993.
= 1 - DR
= 1 - 0.73 = 0.27

Step 5: E = the estimated total 1979-1993 crop-hail loss in the six county target area if there had been no cloud seeding in the target area.
= C/(1-D)
= ($164,413,038)/(1-0.27)
= $225,223,340

Step 6: F = the estimated total 1979-1993 crop hail loss savings in the six county target area.
= E - C
= $225,223,340 - $164,413,038
= $60,810,302

Step 7: G = the total 1979-1993 funding for the Western Kansas Weather Modification Program
= $3,292,270

Step 8: H = the estimated total 1979-1993 funding for the six county target area portion of the Western Kansas Weather Modification Program.
= (G/average number of participant counties) x 6
= ($3,292,270 / 12.27) x 6
= $1,609,912

Step 9: EV = the estimated total 1979-1993 economic value of the cloud seeding activities to suppress hail for all crops in the six county target area.
= F - H
= $60,810,302 - $1,609,912
= $59,200,390

The estimated economic value of the Hail Suppression Component of the cloud seeding activities for all crops in the six county target area was approximately $60,000,000 for the 1979-1993 time period and represented a benefit to cost ratio of 37 to 1. It should be noted that the above estimate of economic value was an underestimate, since it did not include hail-damage savings for dwellings or personal property. Also, the Kansas Department of Wildlife and Parks did not have any estimate of annual wildlife losses due to hail in the target area. Hence, it was not possible to enumerate the wildlife benefits that have resulted from the cloud seeding activities in the target area from 1979-1993.

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"REVIEWED"

GENERATION OF ICE NUCLEUS AEROSOLS BY SOLUTION AND PYROTECHNIC COMBUSTION

William G. Finnegan
Atmospheric Sciences Center, Desert Research Institute
Reno, Nevada 89512-1095

Abstract. Combustion of acetone solutions of AgI and various chemical solubilizers and additives is used to generate ice nucleus aerosols for weather modification research, development and field use Nucleus chemical compositions have varied from AgI itself to 2AgI-NaI, and 2AgI-KI, to Ag(C1)I and to Ag(C1)I-x NaCl (where x has varied from 0.125 to 5), over time.

Combustion of pyrotechnics to produce nucleus aerosols containing AgI is also widely used. Silver iodide and silver chloroiodide "contact" nuclei have been the most often employed. More recent developments have led to the generation of Ag(C1)I nucleants containing soluble salts, which function by rapid condensation-freezing mechanisms, rather than the cloud droplet "contact" mechanism.

These research and development efforts over a 50 years period have led to a better understanding of the relationships between ice nucleus compositions, activities, and the rates and mechanisms of ice crystal formation. Ice nucleus aerosols of optimum utility for field applications are now possible of generation.

1. INTRODUCTION

The chronology of the development of silver iodide containing chemical compositions and aerosols for use in weather modification activities traces an interesting sequence of mixed research and development efforts conducted over a period of fifty years. That a seemingly simple R and D effort should have taken this length of time is perhaps understandable if one considers the multi- and interdisciplinary nature of cloud seeding programs, the development of cloud chambers and alternate attempts to characterize these aerosols and the unfolding understanding of how various chemical variants of the basic AgI aerosol function in cloud. It would appear now, that the end of the program is in sight.

This article considers only pyrotechnic and solution combustion compositions and ice nucleus activity spectra that have been published and that the author is personally familiar with. Many other aerosol generation systems and devices are in current usage.

2. CHRONOLOGY

The discovery of the utility of silver iodide as an ice nucleus by Dr. Bernard Vonnegut at the General Electric Co., Schenectady, New York, (Vonnegut, 1848), followed the discovery by Vincent J. Schaefer that solid carbon dioxide ("dry ice") would induce the formation of ice crystals in a supercooled cloud (Schaefer, 1946). The initial aerosol generation system was the combustion of an acetone solution of silver iodide, using ammonium iodide (NH_4I) as the solubilizing agent (Vonnegut, 1949). The product of combustion was relatively pure AgI, contaminated only by trace amounts of hygroscopic salts from the original AgI preparation, which are co-precipitated with the AgI.

In 1950, however, Dr. Vonnegut published on an acetone combustion system in which sodium iodide, NaI, was used as the solubilizing agent for AgI in acetone (Vonnegut, 1950). The product aerosol was now 2AgI-NaI, rather than AgI, since NaI is not destroyed by combustion, as is NH_4I. The 2AgI-NaI aerosol, as cloud chamber studies at water saturation in a droplet cloud have shown, was not an improvement over the AgI aerosol in terms of ice nucleus activity. These results however, do not imply that the 2AgI-NaI aerosol is less effective in atmospheric application than the AgI aerosol. Other than the occasional use of the 2AgI-KI aerosol from the AgI-KI-acetone combustion system, there were no changes in nucleus compositions from solution combustion until 1979.

The development of large cloud chambers, primarily at the Colorado State University, Department of Atmospheric Science, initiated the determination of ice nucleus activity spectra as a function of temperature in the 1960s, (Grant and Steele, 1966). In subsequent response to requests for ice nuclei with higher activities, the generation of AgI aerosols from the AgI-NH_4I-acetone-water combustion system was reintroduced in 1970 (Finnegan, et al 1971), and became the nucleus of choice for field programs.

3. SOLUTION COMBUSTION GENERATION

A discovery by Thomas W. Slusher, Nuclei Engineering Inc., Lewisville, Colorado, (Slusher, 1978) showed that the addition of an organic chlorine compound to pyrotechnic generators of AgI aerosols improved the activity of the aerosol nuclei significantly. This led to new research on ice nuclei generation by acetone solution combustion. In 1979 a study was initiated on the synthesis and characterization of AgI-AgCl solid solution nucleus aerosols by solution combustion. An increase in ice nucleus activity was expected for this nucleus composition, based on the work of Slusher, and on the prevailing concept of an improved structure match of nuclei with ice (Vonnegut 1947, Vonnegut and Chessin, 1977) that would result from the addition of chlorine atoms into the AgI structure lattice. The research program was designed primarily, however, to address the mechanism of ice crystal formation for this mixed AgI-AgCl nucleus, as well as AgI itself. (DeMott, 1982, DeMott et al 1983). The mechanism of ice crystal formation for these two nucleus compositions was unequivocally established as a sequence of steps starting with the Brownian scavenging of nuclei by cloud droplets, followed by droplet freezing, and the growth of ice crystals, at temperatures of from -5°C to -16°C.

The second phase in the study of the rates and mechanisms of ice crystal formation, and activities of ice nucleus aerosols at the cloud simulation laboratory at Colorado State University concerned the 2AgI-NaI nucleus (Vonnegut, 1950). This nucleus aerosol, generated by combustion of its acetone solution, has been used world-wide since its disclosure and is still in use in several large field programs. Cloud chamber investigations (Blumenstein et al, 1987) demonstrated that, at water saturation in a droplet cloud, the ice nucleus activity of this nucleus was low at temperatures above -12°C, compared to the basic AgI aerosol (DeMott et al, 1983), its threshold temperature for activity was below -6°C and the rate of ice crystal formation for this nucleus was very slow. Cloud chamber tests showed that complete ice crystal formation and fallout required an hour or more at -10°C and -12°C. Correcting for aerosol dilution by cloud air introduction, the process should have taken about 2 hours. The mechanism of ice crystal formation was condensation followed by freezing as expected, but the reason for the very slow rate process and low activity was not elucidated until a later date. The second step in the formation of ice crystals, following water vapor absorption, is the actual ice nucleation step, slowed markedly by the large amount of NaI present. The large I^- ion concentration enhances water molecule dipole-dipole interactions, while supressing the hydrogen bonded structure of water molecules associated with Ag^+ ions on the AgI particle surface. This hinders and slows the nucleation mechanism (Finnegan 1998).

The third phase in the program was undertaken to overcome the low activity, poor threshold temperature and slow ice crystal formation rate of the 2AgI-NaI nucleus and produce a fast functioning, condensation-freezing nucleant with a high ice nucleus activity at temperatures above -12°C. Since the alkali metal iodides solubilize AgI in water at high concentrations (as well as in acetone) the difficulties were presumed to be due, at the time, to the alkali iodide present in relatively high concentrations in the 2AgI-NaI and 2AgI-KI nuclei, either destroying active sites or forming relatively stable complexes with the AgI (Burkardt et al 1970).

The alkali metal chlorides do not solubilize or form complexes with AgI, and methods of synthesizing composite nuclei compositions such as Ag(Cl)I x NaCl where x was varied from 0.5 to 5 were investigated (Feng and Finnegan, 1989). The NaCl was generated by adding sodium perchlorate ($NaClO_4$) in varying amounts to the AgI-0.5 NH_4I-NH_4ClO_4-acetone-water combustion solution of

DeMott (1983). During combustion, the $NaClO_4$ additive is reduced to NaCl. The mechanism of ice crystal formation was, as expected, found to be condensation followed by freezing. The optimal composition for activity and rate of ice crystal formation was found to be Ag(Cl)I-4.0 NaCl. Nuclei particles of this composition have salt quantities attached which can rapidly form dilute salt solutions of 10^{-3} molar concentration or less at water saturation. Particles with smaller quantities of attached salt form solution droplets of higher salt concentration, heading to lower rates of nucleation and lower yields of ice crystals. This is a manifestation of the Kelvin effect (Pruppacher and Klett, 1978). Composite nuclei of AgI or Ag(Cl)I, and a soluble salt, have slower rates of nucleation than AgI or Ag(Cl)I nuclei (Finnegan 1998). The dramatic increases in activities and rates of ice crystal formation observed for this family of ice nucleus aerosols confirmed the hypothesis that Ag(Cl)I-xNaCl aerosols would be superior to 2AgI-NaI aerosols for field application, in terms of activities and rates of ice crystal formation. More recent studies have shown that for generation of Ag(Cl)I-0.5 NaCl aerosol, combustion of acetone solutions of AgI-0.5NaI-0.4 $C_6H_4Cl_2$ (paradichlorobenzene) is a better generation system. The AgI-0.5NaI-0.4 $C_6H_4Cl_2$ acetone generator solution and the AgI-0.5 NH_4I-0.3 NH_4ClO_4-0.5 $NaClO_4$-acetone-water generator solution, on combustion, give identical products with the same activities and rates of ice crystal formation. Elmination of the NH_4I reduces or eliminates solution corrosion of metals other than stainless steel.

On conclusion of these investigations using acetone solution combustion techniques for studying correlations of chemical composition with rates and mechanisms of ice crystal formation and nucleus activities, no further investigations into nucleant aerosol chemical compositions were conducted by the author until 1998. At this time, the author was asked to assist in the establishment of a facility to manufacture pyrotechnic generators of ice nucleus aerosols for use in the Texas weather modification programs, and to devise suitable compositions for efficient operations.

4. PYROTECHNIC COMPOSITIONS

The generation of AgI containing ice nucleus aerosols by pyrotechnic combustion in the United States was first demonstrated by Thomas J. Henderson, Atmospherics Inc., who used red road flares to which small amounts of AgI had been added for orographic cloud seeding in the Kings Canyon in the Sierra Nevada mountains of California. (Henderson, 1958). Ice nucleus activity testing during a Yellowstone Field Research Program sponsored by Vincent Schaefer, demonstrated the formation of copious quantities of ice crystals from the aerosol from these flares (T.J. Henderson, private communication). Also in 1958, the discovery that silver iodate, ($AgIO_3$) could be used as an oxidizer in pyrotechnic formulations to generate AgI aerosols was made and patented (Burkardt et al 1962). On combustion, the $AgIO_3$ is reduced to AgI, which is vaporized, expelled and recondensed to form the aerosol. The use of $AgIO_3$ as an oxidizer in pyrotechnics and a source of AgI was exploited by the Naval Weapons Center, China Lake, California. Initially, several varieties of large cast composite pyrotechnic generators were developed for use in Project Stormfury, a hurricane seeding program (Vetter et al, 1970). Subsequently, the program changed over to the development of pressed composite pyrotechnic formulations to satisfy the need for smaller, more efficient generating devices. This change led to the development of the LW-83 (TB-1) composition consisting of 78% $AgIO_3$, 12% Al, 4% Mg, and 6% epoxy resin binder (St. Amand et al,1970). This formulation is still in use, on occasion, today. The fortuitous discovery by Thomas W. Slusher, of Nuclei Engineering Inc., that the ice nucleus activity of the combustion aerosols from the Navy TB-1 composite pyrotechnic could be significantly increased by the addition of small amounts of organic compounds containing chlorine to the pyrotechnic formulation (Slusher, 1978, Sax et al 1978) was an important contribution to ice nucleus aerosol generation technology. This discovery was interpreted to confirm that the structure match of nucleant and ice was improved by the conversion of the AgI crystal structure to an Ag(Cl)I species, thus improving the ice nucleus activity.

High $AgIO_3$ type pyrotechnic compositions that generate active ice nucleus aerosols, that function rapidly by the condensation-freezing mechanism, have apparently not been developed and characterized for field use. To this end, and to compliment the Navy TB-1 and the NEI TB-I with HCB compositions, the Concho Cartridge, Co. Inc., of San Angelo, Texas can now produce the BF-1 20g. ejectable pyrotechnic, in the 20mm cartridge configuration. This pyrotechnic is formulated to generate, on combustion, an Ag(Cl)I-0.5 NaCl nucleus aerosol. The ice nucleus activity of this aerosol, as determined in the isothermal cloud chamber at Colorado State University is 4.98 x 10^9 and 5.56 x 10^{10} at -6°C and 2.20-6.36 x 10^{12}. These values compare favorably with those reported for the NEI TB-1 with HCB (Sax et al 1979).

Pyrotechnic flare compositions need to be further improved in order to decrease coagulation, and yield nucleus aerosols with higher efficiencies of aerosol generation, high ice nucleus activity and rapid rates of ice crystal formation. This improvement can be achieved. The Russian silverspare pyrotechnic composition, used in the Swiss hail suppression program Grossversuch IV is a low AgI content flare. On combustion it produces an aerosol with excellent ice nucleus activity at warm temperatures and which functions rapidly by a condensation-freezing mechanism (Federer and Schneider, 1981). A development program to formulate similar high efficiency pyrotechnics is currently underway at the Concho Cartridge Co., Inc. of San Angelo, Texas.

5. DISCUSSION

The research program at Colorado State University's Cloud Simulation and Aerosol Laboratory had benefits beyond the elucidation of the relationships between nucleant chemical compositions, ice nucleus activities, and the rates and mechanisms of ice crystal formation. The emphasis on nucleus aerosol generation by combustion of acetone solutions enabled more rapid progress to be made, than could be achieved by other techniques. The program has led to the wide usage of the Ag(Cl) I-0.5 NaCl nucleus composition, (The Cl to I ratio in theAg(Cl)I nucleant is approximately 22:78), for field programs. The Kansas hail suppression program and the hail suppression program in France (Dessens et al 1998) use this nucleus aerosol with documented success. The hail suppression programs in North Dakota (Langerud and Moen, 1998) and in Alberta Province, Canada use a modification of this nucleus. The winter orographic cloud seeding program in the Kaweah basin of the Sierra Nevada mountains of California, conducted by Thomas J. Henderson of Atmospherics Inc., uses this nucleus and is accumulating data on its utility relative to that of the AgI contact nucleus from the AgI-NH_4I-acetone-water combustion system.

The identification of AgI and Ag(Cl)I as "contact" nuclei having a rate of ice crystal formation which is a function of the cloud droplet concentration, was important mechanistically. In hindsight this finding should not have been taken as a recommendation for the use of these nuclei over that of the 2AgI-NaI nuclei, especially for winter orographic cloud seeding. The superior activity of the contact nuclei is counterbalanced by their slow contact rate with cloud droplet concentrations of ~200 per cubic centimeter. Contact nuclei can, however, function rapidly to produce ice crystals by exposure to water supersaturations providing that they are generated, together with substantial quantities of water vapor, at temperatures of -6°C and below (Finnegan and Pitter, 1988, DeMott, 1995). This can often be accomplished by locating acetone burning generators at appropriate positions upwind of the target area. The 2AgI-NaI and 2AgI-KI nuclei can also function rapidly on exposure to transient water supersaturations (Blumeinstein, 1987) and should demonstrate rapid ice crystal formation rates on passing through cold cloud bases.

Information gained on new nucleant compositions generated by solution combustion concerning activities, mechanisms and rates of ice crystal formation can be translated to pyrotechnic combustion products. Proper attention must be paid to the pyrotechnic chemistry, to the arts and science of pyrotechnic manufacture, and to the limitations of pyrotechnic combustion for the translatation to be successful. One of the difficulties encountered in the use of pyrotechnics is the relatively high rate of aerosol generation from pyrotechnic formulations containing high concentrations of $AgIO_3$ as the oxidizer. The concentration of ice nucleus particles in the "smoke" or exhaust plume is extraordinarily high, which enhances coagulation or aggregation of the particles. This process has led to a serious misconception concerning the ice nucleus activities of pyrotechnic aerosols in field applications. Coagulation of the aerosol from the high $AgIO_3$ formulation pyrotechnics, such as the Navy TB-1 and the NEI- TB-1 with hexachlorobenzene, reduces the activity (the number of particles, per gram of nucleant, of 200 to 400 Angstroms diameter which are responsible for ice crystal formation) by about two orders of magnitude. In other words, 99% of the potentially useful nuclei particles are removed by coagulation in the pyrotechnic exhaust. This was shown, in cloud chamber tests, by comparing ice nuclei activities from NEI TB-1 combustion aerosol generated above the wind tunnel fan and the air flow straighteners, with those activities from samples of the aerosol generated below the fan at the entrance to the wind tunnel. The air flow speed for these tests was ~110 miles per hour or "max fan speed". At -20°C, the activity of the aerosol generated above the fan in laminar flow air was 1x 10^{13} IC/gram. The activity of the aerosol generated below the fan was ~1x10^{15} IC/gram. Rapid dilution and temperature quench, leading to decreased coagulation can account for the increase in activity of the aerosol generated below the fan (unreported data from the Cloud Simulation and Aerosol Laboratory, Colorado State University). Pyrotechnics burning in free fall or in-place on an aircraft wing might be expected to resemble those burning in the laminar air flow in the CSU wind tunnel. If so, the practice of using high $AgIO_3$ content burn-in-place protechnics on aircraft to inject large quantities of AgI orAg(Cl)I aerosol for situations requiring such treatment, can be seen to be of little value when coagulation of the aerosol reduces the nucleant output by two orders of magnitude.

Considering this occurrence, together with the fact that different nucleus compositions may function by different mechanisms with different rates and activities, the practice of evaluating field programs or of comparing field programs using only the total weight of silver iodide dispensed per cloud or per season (See for example, Kessler, 1998), should be reconsidered.

Another misconception, still encountered on occasion, is that information from laboratory determinations of activities, and rates and mechanisms of ice crystal formation does not apply to nucleus aerosols used in the "real" atmosphere. Claims are made that nuclei can and will function by sublimation (direct vapor to ice, without the formation of an intermediate liquid phase) to produce the desired results. There is no reason to suspect that heterogeneous ice nuclei will not function by the mechanisms determined in chamber characterizations when generated in the atmosphere. For example, the rapid nucleation, observed when AgI nuclei (of any type) are exposed to transient supersaturations with respect to liquid water in laboratory studies (Blumenstein et al 1987, Feng and Finnegan, 1989) are also observed when AgI aerosols are generated in supercooled fogs from acetone solution combustion (Finnegan and Pitter 1988). Moreover, depositional nucleation, according to N. Fletcher (1962) can occur only on substrates which are completely insoluble in water. Silver iodide has a limited but finite solubility in water of ~ one part in 10^9 parts of water. Wetting AgI particles leads to rapid solution, ionization of the dissolved AgI, and equilibrium formation of surface patches of hydrated Ag^+ and I^- ions on the particles (de Keizer and Lyklema 1981). This leads to hydrophilicity of the particles and the freezing mechanism described by Finnegan (1998), for immersed particles. Studies (Corrin and Barchet 1970, Zettlemoyer et al 1961, Burstein,1955, and Tcheurekdjian, et al,1964) have demonstrated that conventionally prepared AgI contains hygroscopic salts co-precipitated during manufacture, which provide hydrophyllic sites sites for water adsorption from the vapor phase, leading to slow nucleation at -20°C at water saturation in a droplet cloud (DeMott et al 1983, Finnegan,1998).

There is no published experimental evidence for a depositional nucleation, and one should not invoke one for AgI nucleus aerosols.

6. CONCLUSIONS

Based on the above information, it would appear that weather modification field programs, either exploratory or operational, would best be conducted using heterogeneous ice nucleus aerosols that function rapidly by a condensation followed by freezing ice crystal formation mechanism, have been tested and shown to have high ice nucleus activity, particularly at temperatures above -10°C and a threshold temperature of activation of -5°C or -6°C. These aerosols should be generatable in a consistently reliable and reproducible manner by either solution combustion or pyrotechnic combustion.

The solution combustion generation process for nucleus aerosols with these desired characteristics has already been achieved. The Ag(Cl)I-0.5 NaCl aerosol is in wide use with documented utility. Minor improvements in ice nucleus activity and rate of ice crystal formation can be made by increasing the NaCl to Ag(Cl)I ratio but at the expense of increased generator maintenance. No further efforts in solution combustion generation of ice nucleus aerosols are contemplated by this author.

The pyrotechnic combustion process for generating ice nucleus aerosols with similarly desirable characteristics is still in a state of development. There appears to be no unanimity of opinion on chemical composition of pyrotechnic to employ. Many of the formulations are proprietary in nature. Problems of functional inconsistency and reliability have been encountered. It is hoped that continued research, development and scientifically conducted field trials will improve the operational utility and value of these ice nucleus generator devices.

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COMPARISONS OF LOHSE WING-TIP NUCLEI GENERATORS AND BURN-IN-PLACE PYROTECHNICS IN THE NORTH DAKOTA CLOUD MODIFICATION PROJECT

Bruce A. Boe
North Dakota Atmospheric Resource Board
State Water Commission
Bismarck, North Dakota 58505

Paul J. DeMott
Department of Atmospheric Sciences
Colorado State University
Fort Collins, Colorado 80523

Abstract. The characteristics of the ice nucleating aerosols produced by the Lohse wing-tip generators are compared to those produced by the Weather Modification Group WMG-1 formulation burn-in-place flares. The relative output and operating cost of each device are examined. The circumstances in which each seeding method is likely to be optimal are explored using simple thermodynamic considerations and a microphysical parcel model. On a cost basis, the WMG-1 pyrotechnic is found to offer an order-of-magnitude advantage at temperatures near -6°C, while the Lohse generator offers an similar advantage at temperatures of -10°C. Some implications for operational hail suppression projects are suggested.

1. BACKGROUND

The North Dakota Cloud Modification Project (NDCMP) is a dual-purpose operational cloud seeding program designed to reduce damaging hailfalls and increase rainfall. In this program, cloud-base seeding aircraft generate glaciogenic nuclei in two ways. Nuclei generators in which acetone-based solutions are burned are attached to the aircraft wing tips, and burn-in-place flares are mounted to racks attached to the trailing edges of the wings (Atmospheric Resource Board 1997).

The purpose of this paper is to examine the relative effectiveness and costs of these two methods. This evaluation is based on the ice-forming properties of the cloud seeding aerosol particles as inferred from laboratory studies of their nucleating properties, and from NDCMP operational seeding procedures.

The characteristics of the two seeding agents used in the NDCMP are described, and comparisons made of total nuclei production rates and cost effectiveness. The application of the seeding agents in the NDCMP hail suppression methodology are also discussed. Numerical parcel model microphysical calculations are used in the latter section, which includes a detailed consideration of the roles of ice formation mechanisms.

2. SEEDING AGENTS AND PROCEDURES

2.1 Lohse Wing-Tip Generators

The Lohse wing-tip generator employed in the NDCMP was tested by DeMott (1997) at the Colorado State University Cloud Simulation and Aerosol Laboratory (CSU SimLab) using an acetone-based seeding solution suggested to NDCMP managers by Richard Stone (Desert Research Institute, University of Nevada, Reno, 1997, personal communication), a formulation of the type described by Feng and Finnegan (1989). This testing entailed collection of the aerosol particles produced by combustion of a particular solution and examination of their ice nucleating ability in the CSU isothermal cloud chamber. Nucleation ability was described by the yield of ice crystals produced per mass of seeding agent burned and examination of the rates of formation of the resulting ice crystals. The detail of the standard and specific procedures used in this experimentation are found in DeMott (1997).

The general procedures and configuration of instruments used are equivalent to those described in a number of previous publications (e.g., Garvey, 1975; DeMott et al., 1983). The testing included the attempt to reproduce, as closely as possible, the in-flight airflow conditions surrounding the Lohse generator during nuclei generation. Operational airflow past the generator was achieved by placing it within a 0.58 m diameter flow tube connected to the base of the CSU vertical wind tunnel. The standard entry for air into the tunnel was partially blocked to accelerate flow through the tube containing the Lohse generator. This differs from some historical tests of airborne solution combustion generators that were conducted within the wind tunnel itself. Maximum airspeed is about 55 m s^{-1} in the wind tunnel. Use of the below-tunnel flow tube method permits a variable range of flow speeds, including higher values. The compromise in this arrangement, used for these Lohse burner tests (and many other airborne generators since the early 1980's) is that the smoke produced by the generator immediately enters the high speed tunnel fan, quickly diluting the concentrated plume. This could reduce possible coagulation, but one can imagine this same effect being induced in flight by aircraft wing-tip vortices.

The solution used currently in the Lohse generator combines acetone, silver iodide, ammonium iodide, sodium perchlorate monohydrate, paradichlorobenzene, and water to produce an ice nucleus of a $AgI_{0.8}Cl_{0.2}$-NaCl formulation (see Table 1). The production of this nucleus follows the methods of Feng and Finnegan (1989).

Table 1. Formulation of Acetone-based Seeding Solution Used in Wing-tip Nuclei Generators in the NDCMP

Quantity	*Ingredient - Composition*
309.10 g	silver iodide - AgI
95.40 g	ammonium iodide - NH_4I
19.35 g	paradichlorobenzene - $C_4H_4Cl_2$
161.85 g	sodium perchlorate monohydrate - $NaClO_4 \cdot H_2O$
< 355 g (12 oz.)	water (added only as needed to get ammonium iodide into solution)

This composition of seeding agent represents a switch from the $AgI_{0.8}Cl_{0.2}$-4NaCl formulation nuclei employed by the NDCMP from 1984-1996. The newer agent is considered to be an improvement over its predecessor because it results in active nuclei at slightly warmer temperatures, while containing 75% less dissolved solids ($NaClO_4 \cdot H_2O$, NH_4ClO_4). This latter trait makes the solution somewhat less corrosive and significantly easier to ignite. The ice formation rates of the new nucleus at a condition of water saturation (standard condition in the isothermal cloud chamber) are slightly slower than the predecessor nuclei, but the mode of ice formation is the same. This mode is condensation-freezing, as found by Feng and Finnegan (1989). This determination is based on a graphical analysis of the ice formation kinetics, as described by DeMott et al. (1983) and Feng and Finnegan (1989).

The essential behavior of a condensation-freezing nucleus is a dependence of ice formation rate on water vapor saturation ratio at any temperature and not on the characteristics of the cloud droplet distribution, as would be the case for contact-freezing nuclei. The freezing rate as a function of water saturation ratio depends on the chemical composition of condensation-freezing nuclei. The freezing rate may be slower at water saturation and below, while much faster in supersaturated conditions.

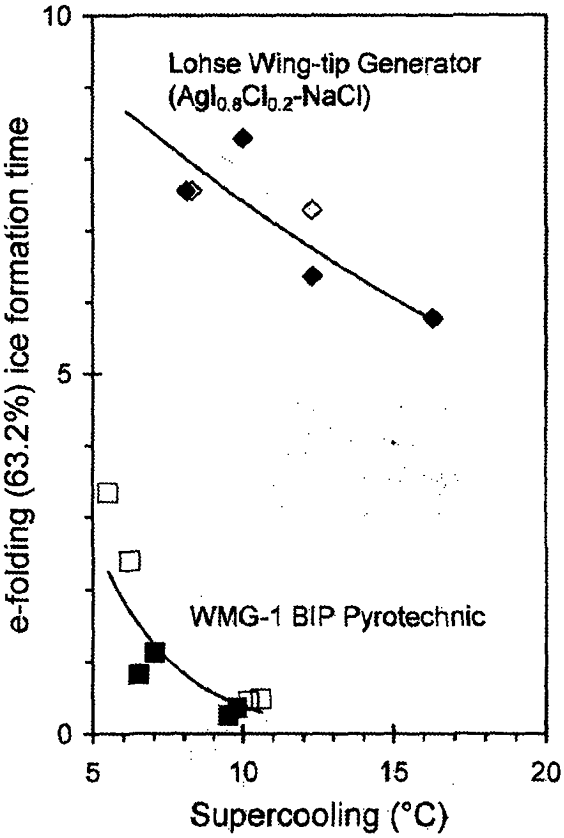

Figure 1. The temperature dependence of e-folding time for ice formation by nuclei from the two generating systems used by cloud-base seeding aircraft in the NDCMP. Values are as measured in the CSU isothermal cloud chamber and represent the negative inverse of the first-order rate constant for ice formation. Closed and open symbols are for clouds with liquid water contents (cloud droplet concentrations) of 1.5 g m^{-3} (~4300 cm^{-3}) and 0.5 g m^{-3} (~2100 cm^{-3}) respectively. The curve fits are simple exponentials.

The dependence of freezing rate on humidity reflects the requirement for diluting excess soluble ions in the condensed phase layers adjacent to the surface of ice nuclei before freezing can occur (Finnegan, 1998). The e-folding times for ice formation (times for 63.2% of ice crystals to form) by $AgI_{0.8}Cl_{0.2}$-NaCl nuclei are plotted as a function of temperature and cloud density in Fig. 1. The raw data are provided in Table 2.The plotted results demonstrate the lack of sensitivity of ice formation times to cloud droplet concentration, thereby confirming the condensation-freezing mechanism. This solution and generator were tested together as described herein early in 1997, to verify that the liquid solution would perform as well or better than its predecessor. The results of the tests conducted with this formulation are compared with the results of the tested flares, described below.

Table 2. Times for formation of 63, 90, and 99% of ice crystal yield as a function of temperature for the nuclei used in the NDCMP

Source	Temp. (°C)	LWC (g m^{-3})	$t_{63\%}$ (min)	$t_{90\%}$ (min)	$t_{99\%}$ (min)
Lohse	-6.0	1.5	5.30	12.2	24.4
	-8.3	1.5	7.55	17.4	34.8
	-10.0	1.5	8.29	19.1	38.2
	-12.3	1.5	6.37	14.7	29.3
	-16.3	1.5	5.77	13.3	26.6
	-8.3	0.5	7.56	17.4	34.8
	-12.3	0.5	7.29	16.8	33.6
WMG-1	-5.5	1.5	3.34	7.69	15.4
	-6.2	1.5	2.39	5.50	11.0
	-6.5	0.5	0.82	1.89	3.78
	-7.1	0.5	1.12	2.56	5.16
	-9.5	0.5	0.25	0.57	1.15
	-9.8	0.5	0.36	0.83	1.66
	-10.2	1.5	0.45	1.04	2.07
	-10.6	1.5	0.48	1.10	2.21

2.2 WMG-1 Burn-in-place Flares

The WMG-1 burn-in-place pyrotechnics, manufactured by the Weather Modification Group of Okotoks, Alberta, Canada, were also tested in the CSU SimLab (DeMott 1995a). The precise formulation of this flare, previously given an SM-1 designation, is proprietary. Though the exact nucleus composition and chemical nature of the soluble salt component of nuclei produced by this flare are unknown to the authors, the behavior of these nuclei in warm cloud can be meaningfully compared to those of the Lohse generator for reasons discussed in section 2.3. As the quantity of seeding agent was known to be 82 g flare, the number of nuclei produced was calculated on the basis of the flare mass consumed. All pyrotechnic flares are tested above the wind tunnel fan following Garvey (1975).

DeMott (1995a) found that the nuclei produced by the WMG-1 formulation also function in a condensation-freezing mode. The ice formation rates were found to be much faster at warmer temperatures (-6°C) than the nuclei produced from the wing-tip generators, presumably due to unresolved physical and/or chemical characteristics of the WMG-1 nuclei. This is demonstrated in Fig. 1, which shows the e-folding times for ice formation of the two nuclei types.

2.3 On cloud chamber ice nuclei comparisons

It has long been recognized that results from the CSU isothermal cloud chamber may not be entirely relevant to the behavior of ice nucleus aerosols in real clouds. Consequently, a comparison of different nucleus compositions based on isothermal cloud chamber yield alone may not give a fair comparison of two different systems. This problem was a past motivation for development of the chemical kinetics methodology for analyzing ice formation rates to discern mechanisms of ice formation in cloud chamber studies (e.g., DeMott et al., 1983). Most standard testing performed at the CSU SimLab since the mid-1980's has attempted, when possible, to make a determination of the dominant ice formation mechanism noted at water saturation. With a knowledge of the predominant ice formation processes, extension of the testing results to real cloud conditions becomes a little more meaningful.

More realistic cloud simulations using the CSU dynamic cloud chamber have provided another means for making meaningful recommendations for field application of ice nucleus aerosols (DeMott et al., 1985; DeMott, 1988). This chamber allows for the simulation of an expanding cloud parcel including cloud formation at warm temperature and ice formation in transient or nearly steady-state supersaturated conditions at lower temperatures. Fully evaluating the different ice formation behaviors using this chamber is possible with appropriate experimental techniques (DeMott, 1995), but not in programs of limited scope and resources (such as is most often supported by the weather modification community). Dynamic cloud chamber simulations were not performed for the aerosols that were the subject of this study. We thus point out two facts from tests performed on other nuclei that are quite relevant to this study. First, DeMott et al. (1985) have shown that the activity of ice nucleus aerosols at supercooled cloud temperatures below about -8°C is oftentimes not very dependent upon the amount of time the aerosols spend in cloud at warmer temperatures.

The ice formation mechanism may be altered by the dynamic cloud processing, but once altered, the time nuclei spend in cloud usually only leads to a slight degradation of ice formation yield. The same result has been obtained for aerosols produced by other ground generators, airborne generators, and even a pyrotechnic (unreported data). These studies and those of DeMott (1988) have also shown that the ice nucleus activity of condensation-freezing nuclei versus temperature in a dynamic cloud parcel bears some relationship to the condensation-freezing rate at water saturation.

For nuclei with very slow freezing rates at water saturation (e.g., 2AgI-KI or 2AgI-NaI, due to excess I^- ions at water saturation), ice formation was greatly enhanced in dynamic chamber processing. Nuclei with very fast freezing rates at water saturation (Ag(Cl)I-4NaCl) showed slightly lower yield at supercooled temperatures warmer than about -12°C in dynamic chamber simulations (DeMott, 1988). This latter observation may relate to the effects of dissolution of the less soluble chemical component, particularly the smaller particles, over the long transit times to low temperatures.

These previous observations provide the basis for the simple assumptions made (in section 4 of this paper) in order to address the full range of expected behaviors of these two NDCMP aerosols in real clouds. Though more information would render the conclusions herein less speculative, we nevertheless believe that the comparison methodology presented in this paper is widely applicable and useful for operational planning.

3. YIELD AND TEMPERATURE

In this section the two seeding methods are compared solely on the basis of the total potential number of ice nuclei produced (yield) versus temperature, as measured in the CSU isothermal cloud chamber. Yield data are typically presented as the number of nuclei produced per gram of AgI or, in the case of a pyrotechnic, per gram of flare mass. Yield values are converted here to production rates per minute and per dollar spent.

3.1 Production Rates

The yield of ice crystals per gram of AgI burned by the Lohse generator and per gram of WMG-1 pyrotechnic mass were measured versus temperature by DeMott (1995a,1997). These nucleation activities are listed in Table 3. Provided that the temporal output of AgI and pyrotechnic mass are known, the nuclei production rates can be calculated and compared.

Table 3. Yield of ice crystals per gram, per minute, and per dollar, as a function of temperature for the nuclei used in the NDCMP

Source	Temp. (°C)	LWC ($g\ m^{-3}$)	Yield (g^{-1})	Yield (min^{-1})	Yield ($US\$^{-1}$)
Lohse	-6.0	1.5	2.5×10^{11}	7.7×10^{12}	9.3×10^{11}
	-6.0	1.5	4.8×10^{11}	1.5×10^{12}	1.8×10^{12}
	-8.1	1.5	2.6×10^{13}	8.0×10^{13}	9.7×10^{13}
	-8.3	1.5	2.8×10^{13}	8.5×10^{13}	1.0×10^{14}
	-8.3	0.5	1.9×10^{13}	7.7×10^{13}	9.4×10^{13}
	-8.3	0.5	1.9×10^{13}	7.4×10^{13}	9.0×10^{13}
	-10.0	1.5	1.3×10^{14}	4.0×10^{14}	4.9×10^{14}
	-10.0	1.5	9.9×10^{13}	3.1×10^{14}	3.7×10^{14}
	-12.0	0.5	1.7×10^{14}	5.4×10^{14}	6.5×10^{14}
	-12.1	0.5	1.5×10^{14}	4.6×10^{14}	5.6×10^{14}
	-12.3	0.5	1.7×10^{14}	5.4×10^{14}	6.5×10^{14}
	-12.3	1.5	2.7×10^{14}	8.4×10^{14}	1.0×10^{15}
	-12.3	1.5	4.2×10^{14}	1.3×10^{15}	1.6×10^{15}
	-16.3	1.5	1.4×10^{15}	4.3×10^{15}	5.2×10^{15}
	-16.3	1.5	1.0×10^{15}	3.2×10^{15}	3.9×10^{15}
WMG-1	-5.5	1.5	2.0×10^{12}	7.5×10^{13}	4.8×10^{12}
	-6.2	1.5	6.6×10^{12}	2.3×10^{14}	1.5×10^{13}
	-6.5	0.5	8.9×10^{12}	3.2×10^{14}	2.0×10^{13}
	-7.1	0.5	9.8×10^{12}	3.4×10^{14}	2.2×10^{13}
	-9.5	0.5	1.6×10^{13}	5.6×10^{14}	3.6×10^{13}
	-9.8	0.5	1.1×10^{13}	4.1×10^{14}	2.6×10^{13}
	-10.2	1.5	1.0×10^{13}	3.7×10^{14}	2.4×10^{13}
	-10.2	1.5	1.1×10^{13}	3.9×10^{14}	2.5×10^{13}

Since 309.1 g AgI is used in mixing each 5 gallon batch of seeding agent for the NDCMP, and since the consumption rate of seeding solution is 3 gal h^{-1}, the

number of grams of silver iodide, M_{GEN}, consumed per minute of generator burn time is expressed by the formula:

$$M_{GEN} = 309.10\,g\,\frac{3\,gal\,h^{-1}}{5\,gal}\,\frac{1h}{60\,min} = 3.091\,g\,min^{-1}$$

Similarly, each WMG-1 burn-in-place (BIP) flare contains 82 g of reagent, and is characterized by a nominal two-minute burn time. The mass of nucleant output from the BIP flare, M_{BIP}, is thus

$$M_{BIP} = \frac{82\,g}{2\,min} = 41\,g\,min^{-1}$$

A comparison of the production rates of the two seeding generators on a per minute basis is presented in Fig. 2, data are given in Table 3 on the previous page.

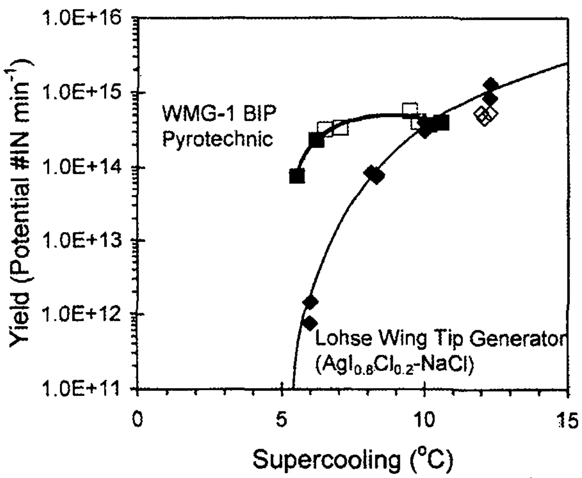

Figure 2. Yield of total potential ice nuclei per minute for $AgI_{0.8}Cl_{0.2}$-NaCl aerosol particles produced by the Lohse generator and the AgI-containing WMG-1 burn-in-place pyrotechnic. Line fits (polynomials) are drawn to distinguish the two series. Open and closed symbols have the same meaning as in Fig. 1.

The WMG-1 BIP flares appear to provide advantageous production rates at all temperatures warmer than about -11°C. The difference in production rates increases with temperature, exceeding a factor of 100 at -6°C. This is because the WMG-1 pyrotechnic nuclei activity is only weakly sensitive to temperatures colder than -6°C, especially when compared to the activity of the nuclei produced by the solution combustion. In hail suppression operations, both wing-tip generators are normally operated, doubling the output of $AgI_{0.8}Cl_{0.2}$-NaCl nuclei. If a single BIP flare is ignited at the same time that both generators are operated, the total output of nuclei from both wing-tip and burn-in-place sources active at -10°C is boosted by 66% to about $1.0x10^{15}$ min^{-1}. However, if one considers relative performance of the nuclei at warmer (perhaps even warm cloud) temperatures such as would typically encountered earlier, lower in the growing cloud turret, the WMG-1 nuclei have a marked advantage in that they will activate at warmer temperatures. For example, at a temperature of -6°C the number of active WMG-1 nuclei is about $2x10^{14}$ g^{-1}, exceeding the Lohse generator production by a factor of 100. In any case, this boost in concentration of active nuclei lasts only as long as the flare burns.

Additional factors related to nucleation rates and mechanisms, cloud dynamics, and microphysical effects must be considered in any meaningful comparison of the different nuclei; these are discussed in section 4.

3.2 Nuclei Production Costs

The use of the Lohse and pyrotechnic generators entail quite different cost factors. During the 1997 NDCMP, a 5-gallons of seeding solution cost $82.00. Computed on a cost per minute basis (again assuming a consumption rate of 3 gal h^{-1}), this works out to $0.82 min^{-1}. Also during the 1997 NDCMP, each WMG-1 BIP flare cost $31.50. With a two minute burn time, this works out to $15.75 min^{-1}. The production rates calculated in section 3.1 are normalized by the production costs, and the costs per dollar are as listed in Table 2 and plotted in Fig. 3. On the basis of a -10°C

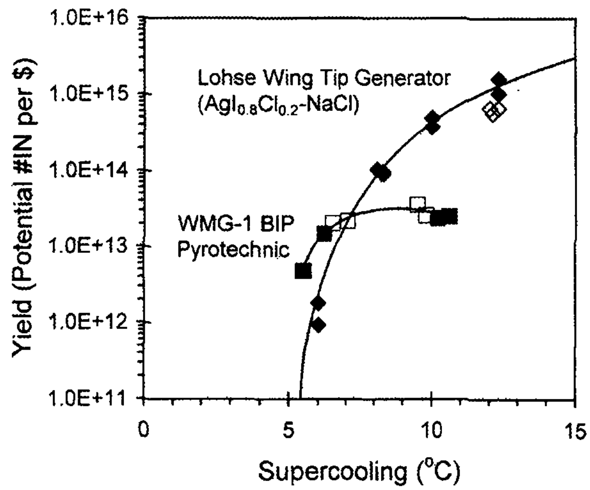

Figure 3. Yield of total potential ice nuclei per dollar expended for $AgI_{0.8}Cl_{0.2}$-NaCl aerosol particles produced by a single Lohse generator versus aerosol particles produced by a single WMG-1 burn-in-place pyrotechnic. Closed and open symbols have the same meaning as in previous figures.

activation temperature, the BIP flare cost 14.5 times more than what a single wing-tip generator cost to operate. However, the -10°C activation temperature is arbitrarily selected for comparing seeding methods because itis a typical cloud temperature at which it is expected that a significant nucleation effect must be achieved in the context of the NDCMP hail suppression conceptual model. Based on Figure 3, the BIP flare is far more cost effective for seeding warmer supercooled cloud regions. This advantage at temperatures warmer than -7°C may be well worth the cost, depending on the microphysical importance of enhanced ice formation at these warmer temperatures. This is further discussed in Sec. 4.

4. HAIL SUPPRESSION AND DYNAMIC NUCLEI RESPONSE CONSIDERATIONS

A rigorous study of the relative merits of wing-tip generators and BIP flares would include a more complete description of nuclei activation characteristics than has yet been obtained, and complete physical descriptions of the processes hypothesized to lead to hail suppression, perhaps integrated with numerical cloud modeling that could resolve some of these effects in different cloud systems on different days. Nevertheless, presently-available information can be used to conduct a simple kinematic analyses of the microphysical seeding effects on air parcels lifted into "typical" clouds, considering NDCMP treatment methods. Resulting insights (see section 5) might improve operational decision-making, especially considering present procedures which are based largely on static nuclei production rates.

The ice formation rates and mechanisms are worthy of additional consideration in the context of the trajectories and seeding aerosol transport times into and within the targeted clouds. It has been noted that the dominant ice formation mechanism in these isothermal cloud chamber studies was found to be condensation-freezing for both nuclei types. However, the activation rates of the Lohse nuclei by this mechanism were found to be significantly slower at water saturation than the WMG-1 BIP nuclei (Fig. 1, Table 2). This could be an additional factor that would moderate the potential nuclei production advantage of the wing-tip generator nuclei in colder cloud regions. However, if freezing rates are limited by the particle solute dilution process, then the time spent by seeded parcels rising in-cloud en route to supercooled regions (where ice can nucleate) could temper the differences in activation times of the two nuclei. Yield might also be altered by the dynamic cloud processing.

Project base-seeding aircraft typically are positioned 500 ft or so below the mean cloud base altitude, in inflow (updraft) speeds on the order of 2.5 m s^{-1} (500 ft min^{-1}), either below rain-free cloud bases, or 3-8 km (2-5 mi) in advance of the leading edge of precipitation (Atmospheric Resource Board 1997). Seeding is conducted in proximity to modest, developing updrafts rather than mature updrafts, as the latter would only serve to rapidly transport the nuclei aloft to the cloud anvil, and would likely not achieve the desired effect. [The interested reader is referred to Smith et al. (1997) for a more detailed description of the NDCMP conceptual model for hail suppression.] Horizontal transport is probably not relevant to ice nuclei activation characteristics, but the vertical transport question can be addressed by some exercises on a thermodynamic diagram. This has been done, and the results again expressed in Table 4.

Table 4.
Nuclei Time from Generation to Activation
Transport from 500 ft below cloud base to the -5°C level by a 500 ft min^{-1} updraft

Surface Temp/ Dew Point (°F)	*Cloud Base Hgt. (kft msl)*	*Mean Cloud Base Temp (°C)*	*Δh, Δt (kft, min)*
61 / 42	5.7	+3.0	4.9, 9.8
77 / 50	7.8	+6.8	7.0, 14.0
86 / 50	9.6	+5.5	6.4, 12.8
95 / 68	7.5	+16.5	14.3, 28.6
86 / 39	12.0	-2.0	2.1, 4.2
68 / 40	8.0	+2.0	3.9, 7.8

The table is based on a fully-mixed subcloud layer, an initial surface pressure of 950 mb, and continuous 500 ft min^{-1} updraft.

A wide range of surface conditions typical of western North Dakota were used to produce Table 4. The shortest transport times (from cloud base to supercooled cloud volume) are most likely with high, colder, cloud bases, which result in atmospheric conditions characterized by less low-level moisture and very warm surface temperatures. While these conditions do occasionally result in high-based thunderstorms, such storms are prone to producing dry microbursts, but not hail.

The numbers in Table 4 are only approximations, however. With a stronger updraft, say 5 m s^{-1} (~1000 ft min^{-1}), the times would be halved. This could easily happen, especially with the higher-dew point conditions, when the convective available potential energy is greater. (The reader is reminded that the clouds of interest are echo-free cumulus congestus, not mature cumulonimbus).

Referring back to Table 2 and Fig. 1, it is seen that compared to the wing-tip generator nuclei the BIP flares have about a 7 min advantage for 63% activation, and up to a 15 min advantage for 90% activation. With reference to Table 3, this rate advantage for the BIP flares should only be realized for colder-based storms with shorter vertical transport times. Shorter transport times are also present in the stronger updrafts associated with more mature cells, but cells at such a stage of maturity are probably not suitable targets for seeding anyway.

There is a possibility that the nucleation mechanism and rates in the atmosphere would be different than in the isothermal cloud chamber studies. It might be expected that water vapor supersaturations in the cloud base region would lead to water uptake (possibly even cloud droplet activation) that speeds the subsequent freezing process at lower temperatures. The ice formation mechanism in such a case would be immersion-freezing, with some fraction of the nuclei activating nearly instantaneously at supercooled temperatures. The active fraction might or might not be the same as measured for condensation-freezing. The process leading to immersion-freezing was not mimicked in the laboratory studies described, although means to do so do exist (e.g., DeMott, 1988 and DeMott et al., 1985).

In the absence of having performed more realistic laboratory cloud simulations, we can only speculate that both nuclei types used for cloud-base treatment in the NDCMP would act as immersion-freezing nuclei with somewhat less efficiency than they do as condensation-freezing nuclei. This would seem most likely to be the case at temperatures warmer than -10°C based on studies of $AgI_{0.8}Cl_{0.2}$-4NaCl nuclei reported by DeMott (1988; 1995b).

To compare the cumulative potential microphysical effects of seeding with the two types of NDCMP nuclei from below cloud base, we use the microphysical parcel model described in Stith et al. (1994). This model has been applied to study natural ice formation processes in North Dakota cumuli. The cloud model requires specification of initial parcel thermodynamic conditions and the parcel trajectory. Liquid and ice particles are nucleated and are allowed to grow and interact. Size distributions are specified within bins and ice crystals are allowed to grow along both *a* and *c* crystal axes. The natural nucleation processes were retained in the seeding simulations, but we consider also ice formation by aerosol particles added by seeding. The model parcel is adiabatic, it never loses water as precipitation, and air is not entrained from nearby cloud parcels.

Two scenarios are modeled to bracket the potential range of seeding effects inside an adiabatic cloud parcel. The best-case scenario is one in which the particles nucleate with the same yield as determined in isothermal cloud chamber tests. This is referred to as the "no rate" simulation. The numbers of ice crystals nucleated as the parcel cools in this case are based on the mass of seeding material per unit volume and a polynomial function fit to the yield data from Table 3. In the worst-case scenario, we assume that the nucleation rates measured in the cloud chamber are also required to form ice at each cloud temperature. This "with rate" case was implemented in the model by fitting a polynomial function to the yield data and applying a temperature dependent rate constant to the yield based on Fig. 1 (where the rate constant is the negative value of the inverse of the e-folding time). The yield and rate constant were adjusted in finite steps at the start of each 1 s model time step. The threshold temperature for any ice formation was taken as -5°C for the $AgI_{0.8}Cl_{0.2}$-NaCl nuclei and -4.5°C for the WMG-1 BIP nuclei.

Initial conditions for simulations were selected in the following manner. Initial concentrations of nuclei entering cloud base were based on a simplified analysis of generator effluent dilution following generation. If particles dilute into a (wing-tip) vortex 30 m in diameter at an aircraft speed of 55 m s^{-1}, then they fill a volume of $3.9 x 10^4$ m^3 in 1 s. If this initial volume expanded at lateral and vertical rates of 1 m s^{-1} for one minute during transport to cloud base, the volume entering cloud base would be about $9.7 x 10^5$ m^3. This volume was taken as that into which the number of grams generated per second was dispersed. It suggests cloud base total nuclei (e.g., yield at -25°C) concentrations of about 5.3 x 10^5 L^{-1} for the nuclei from a single Lohse burner and 9.4 x 10^3 L^{-1} for the pyrotechnic nuclei. A constant updraft rate of ~2.5 m s^{-1} (500 ft/min) carried parcels from cloud base (+5°C) to the -15°C cloud level.

Some basic results of the model simulations for each nucleant are summarized in Table 5. Ice crystal concentrations, maximum ice crystal dimensions, and ice water content (IWC) are included.

The full ice crystal size distributions at the -10°C level in the four simulations are shown in Figure 4. Several results stand out. First, greater numbers of larger ice crystals are predicted to form in all scenarios when seeding is done with the WMG-1 BIP nuclei. The presence of these larger crystals is clearly due to the maximization of the BIP flare yield at warmer cloud temperatures. The particles have longer times to grow. A consequence is that higher IWC is produced in the parcel in BIP flare seeding. This advantage for the BIP flare is particularly evident at the -10°C level. Such conversion of cloud water to ice at a warmer temperature is a desirable trait for a nucleant used for hail suppression. The Lohse nuclei are predicted to form more ice crystals in the parcel in the best-case "no rate" scenario of instantaneous nucleation at each cloud temperature. Since the ice formation rates in the worst-case are slower for the Lohse nuclei, the ice crystal concentrations are lowered more (two to three orders of magnitude) for these aerosols, as compared to the WMG-1 BIP flare nuclei, which are lowered by one order of magnitude in comparison to the best-case scenario for a rising cloud parcel. Nevertheless, as the "no rate" scenario seems

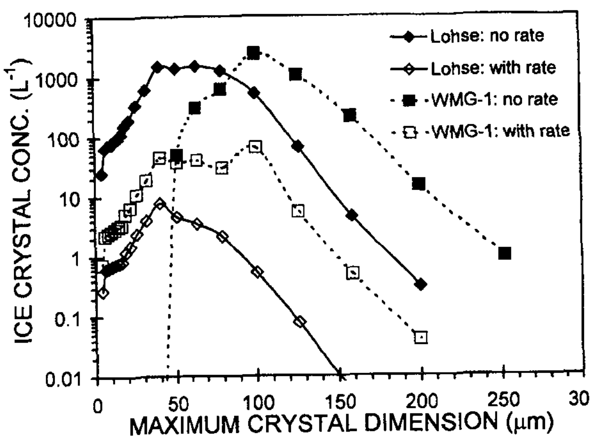

Figure 4. Ice crystal size distributions at -10°C in parcel simulations using Lohse and WMG-1 nuclei, with assumptions on the spontaneity of the ice formation. Simulation conditions and further description are given in the text. Data points are plotted at the midpoints of bins (not shown) of variable size. As shown herein, size is the maximum dimension (a or c-axis) of the ice crystals.

more parcel. realistic, based on past laboratory studies (see section 2.3), and since most target clouds probably penetrate the -10°C level, the improvements suggested for the BIP flare may not justify the additional costs.

On the other hand, the cost of the BIP flares may be justified as a better assurance of warmer temperature cloud effects for clouds with a wide range of base/top temperatures and updraft speeds. To guarantee success regardless of cost, the simulations would seem to support the case for the use of a BIP flare in combination with solution combustion generators.

Table 4. Simulated Ice Crystal Concentrations, Diameters, and Ice Water Contents

Source	*Simulation Type*	*Temp. (°C)*	*Conc. (L^{-1})*	*D_{avg} (μm)*	*IWC ($g\ m^{-3}$)*
Lohse	"with rate"	-10	9.7	51	.001
WMG-1	"with rate"	-10	86.7	69	.017
Lohse	"no rate"	-10	4,120	52	0.25
WMG-1	"no rate"	-10	2,100	94	1.05
Lohse	"with rate"	-15	13.1	152	1.00
WMG-1	"with rate"	-15	384	139	2.45
Lohse	"no rate"	-15	26,600	72	3.25
WMG-1	"no rate"	-15	1,900	150	3.26

5. SUMMARY

The following points summarize this paper.

a. The production rates of nuclei (min^{-1}) of the WMG-1 BIP flares exceed those of a single Lohse wing-tip generator (producing $AgI_{0.8}Cl_{0.2}$-NaCl nuclei) at isothermal cloud chamber test temperatures warmer than -10°C. The difference exceeds a factor of 100 at -6°C in water saturated conditions.

b. On a per dollar basis (1997 costs), the BIP flare outperforms a single wing-tip generator by an order of magnitude at -6°C. A wing-tip generator outperforms the BIP flares by an order of magnitude on a cost basis at -10°C. The two generation methods have equal cost factors for producing ice nuclei effective at about -7°C on the basis of CSU isothermal cloud chamber results.

c. The base costs of flight operations per minute were $1.22 for reconnaissance (flight without any seeding), $2.04 for single-generator seeding, $2.86 for dual-generator seeding, and $18.61 for dual-generator seeding while burning a single BIP flare. Thus, the use of flares adds significantly to the operational costs.

d. Both nuclei types activate ice formation by a condensation freezing mechanism. At water saturation, the BIP nuclei are faster-acting. This difference may not exist in seeded cumulus updrafts since exposure to water vapor supersaturation would tend to increase water uptake and indirectly speed the rate-determining freezing process for both nuclei.

e. Microphysical model simulations to bracket best- and worst-case expected seeding effects using the two types of nuclei suggest that the use of the BIP nuclei may be warranted as a means of most effectively converting cloud water into larger ice crystals at the earliest stage of cloud development. A combination of the two generator types may offer the best, if not the most cost-effective strategy.

It must be reiterated that the laboratory studies did not exactly mimic the operational seeding. In particular, the possible enhancement or degradation of ice nuclei yield under dynamic cloud conditions was not investigated. Also, the cloud model used only simulated an "idealized" cloud parcel, and did not project the ultimate effects on precipitation and hail production. Nevertheless, this study offers a basis for comparing seeding techniques and making operational decisions that should be applicable to any program and for any generators and flares that have been tested in the laboratory.

In the context of NDCMP base seeding operations, two wing-tip generators are always operated when seeding for hail suppression purposes. In addition, multiple aircraft are frequently employed in treating a single convective storm complex. Given the cost per minute of seeding time reported herein, six cloud base seeding aircraft can be flown with both Lohse generators running for about the same price as a burning a single WMG-1 BIP flare. Nevertheless, the faster (and warmer) activation of the WMG-1 BIP nuclei makes it an attractive addition to the seeding arsenal. In part due to the exploratory investigations reported herein, seeding rates employed in the NDCMP are presently being re-examined. Changes in policy and procedure are probable.

ACKNOWLEDGMENTS

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Chaff Tagging for Tracking the Evolution of Cloud Parcels

Roger F. Reinking[1#], Roelof T. Bruintjes[2], Bruce W. Bartram[1], Brad W. Orr[1], and Brooks E. Martner[1]

[1]NOAA/ERL/Environmental Technology Laboratory, Boulder, CO
[2]Research Applications Program, National Center for Atmospheric Research, Boulder, CO

Abstract. A means to mark and track a moving and mixing volume within a cloud is useful for estimating the transport and dispersion of seeding material or other aerosols and thus for determining where and when the microphysical effects of the aerosols should occur. A proven approach has been to release and track chaff into a cloud and track it with circular polarization radar to estimate the rates of dispersion, loft, and dilution of ingested aerosol, as well as the filling of the cloud volume. The chaff, an effective tracer, is separable from the cloud because it strongly depolarizes the radar's signal. A primary disadvantage of this cloud-volume-filling approach is that radar measurements of the microphysical evolution of the tracked cloud parcels may be masked by the chaff itself. To measure transport and dispersion in cloud and simultaneously unambiguously examine the microphysical evolution in the same volume, a refined approach was devised to tag but not fill the cloud volume with chaff. Several experimental designs for chaff tagging are proposed for stratiform or gravity-wave clouds, and for cumuliform clouds. The tagging technique will be more difficult to apply in convective clouds and is not yet tested. However, a "parallel lines" experiment designed for stratiform clouds was tested with hygroscopic seeding in a wave cloud with intrusions of convective cloud. The chaff lines were tracked for about one hour despite some ingestion by convective elements. This demonstrated that a seeded cloud volume could be bracketed and tracked effectively. A hygroscopic seeding signature, anticipated to appear as a line of enhanced reflectivity along a seeded flight path between the chaff lines, was not detected. A "tagged circle" experiment with silver iodide seeding was conducted in a precipitating wave cloud. A seeded circle was tagged with arcs of chaff, allowing it to be tracked efficiently. A seeding effect was indicated along the circular seeded path between the chaff arcs as signatures of enhanced reflectivity and values of depolarization indicative of pristine, new ice crystals. The results of these experiments demonstrate the potential of the chaff tagging technique.

1. INTRODUCTION

Hobbs et al. (1981) demonstrated that a standard radar measuring only reflectivity could be used to detect snow plumes generated by seeding supercooled stratus with dry ice from an aircraft. That study had the advantage of simplicity. A shallow (1-2 km deep), very uniform, all-liquid cloud was advecting over a vertically pointing 8.6 mm radar. Although penetrations of the seeded track with the instrumented aircraft did document the presence and concentrations of the resulting ice particles, the study was at a disadvantage due to the lack of radar volume scanning and a means to explicitly mark and track the space-time evolution of the whole seeded track. In most situations, the cloud dynamics and microphysics are more complicated, so a means to mark and track the seeded cloud volume provides a very strong advantage for estimating the transport and dispersion of seeding material and the consequent microphysical effects of seeding.

A technique called TRACIR (Tracking Air with Circular-polarization Radar) has proven useful for tracking parcels of air and measuring the time-history of cloud volume filling by aerosols such as seeding material within both convective and stratiform clouds (Martner and Kropfli 1989, Martner et al. 1992, Reinking and Martner 1996, Stith et al. 1996). Chaff, the material that is tracked, is comprised of aluminum-coated glass filaments about 25 μm in diameter that can be dispersed in great numbers and are designed to be detected by radars with circular polarization. Chaff filaments approximately circulate and mix with the air, since their settling rate is only ~0.25 m s^{-1}.

#Corresponding author's address: Dr. Roger F. Reinking, NOAA/ERL/ET6, 325 Broadway, Boulder CO 80302; rreinking@etl.noaa.gov.

The detectability of chaff is enhanced by cutting the filaments to half the wavelength of the tracking radar to make them resonant dipoles with large radar cross sections. Chaff can be cut to the appropriate length as it is released from an aircraft or the ground. Depolarization rather than the reflectivity of a radar's signal is used to detect the chaff inside clouds. Our experience indicates that chaff in the high concentrations that immediately follow release will have reflectivities of ~20 dBZ, and that these reflectivities will diminish with dilution. Therefore, the reflectivity of chaff normally becomes partially or totally obscured by the cloud reflectivity, but strong depolarization of the radar's signal by the chaff fibers allows them to be detected within a field of higher reflectivities.

The orientation of the fibers does not affect the signal, nor hence, derived concentrations, if the observing radar uses circular polarization. The effect is measured as the circular depolarization ratio (CDR), which is the ratio of energy returned in the radar's receiving cross channel to energy returned in the main channel from a circularly polarized signal transmitted in the main channel. Theoretically, for chaff in clear air, CDR = 0 dB. This depolarization value is quite different from that caused by hydrometeors other than hail. In practice, chaff has been identified with CDR values ranging from +4 to -14 dB, in clouds with reflectivities up to 30-35 dBZ (e.g., Reinking and Martner 1996). The lesser (more negative) depolarizations usually result from dilution and are identified as chaff by spatial and temporal continuity of the signal. The NOAA/ETL X-band (3.2 cm) circular-dual-polarization Doppler radar was used in the noted studies that detail TRACIR, and in the present study.

The standard approach has been to release the chaff filaments along with seeding material from an aircraft or the ground, to follow the transport, dispersion and cloud volume filling by both. Alternatively, chaff is released alone to examine how seeding material might disperse within a certain type of cloud if it were to be seeded, for example, or how pollutants might be ingested from the planetary boundary layer. This approach provides measures of the rates of dispersion, loft, and dilution of the ingested material, as well as the volume filling. (In this paper, "volume filling" refers to the volume of a cloud rather than radar-beam filling, except as noted.) A primary disadvantage of this approach is that radar measurements of the microphysical evolution of the tracked volume may be masked by the chaff itself. Microphysical evolution can be measured as changes in cloud reflectivity, or with more specificity as changes in cloud depolarization. Reflectivity, Z_e, measures the combined effect of hydrometeor size and concentration. However, chaff does have reflectivity, and although this reflectivity is usually slight enough to be obscured by the cloud's reflectivity, it may still contaminate or at least introduce some uncertainty in reflectivity as a measure of microphysical evolution. A general depolarization ratio may be defined as

$$DR = 10 \log (P_{cr} / P_{co})$$

where P_{co} is the power returned in the main channel and P_{cr} is the power returned in the cross channel. Any of various DRs are determined by hydrometer shape, settling orientation, and bulk density, and the polarization state of the transmitted radiation (circular, linear, elliptical). Therefore, the DRs can provide estimates of hydrometeor type or phase (ice vs. liquid), and the evolution thereof (Reinking et al. 1996, 1997). Chaff is tracked by measuring CDR, so any measure of the hydrometeor type or phase using CDR or related polarization parameters in the same cloud volume introduces some ambiguity into hydrometeor identification unless the values of CDR characterizing the hydrometeors are substantially different from the values of CDR characterizing chaff. For some ice particle types the difference is substantial; for others it is not. The differentiation can be enhanced via measurement with a radar of significantly different wavelength than that for which the chaff length is cut. This approach can be useful, but it is tricky.

To optimally measure transport and dispersion in cloud via TRACIR and simultaneously examine microphysical evolution, a modified experimental design is required. One approach might be to pair similar clouds with proximity, releasing chaff into one and not into the other, under the assumption that each cloud of the pair will behave similarly without seeding, and similarly with seeding if both clouds are treated. The standard volume-filling approach to chaff tracking would be employed in one cloud to measure loft and dispersion, and the other would be examined with a radar for microphysical evolution, assuming loft and dispersion of seeding material in this cloud would be similar to that in the one with chaff. In this version of a target/control experiment, both clouds of the pair would be seeded, or not seeded, but chaff would be released only into one. A sufficient sample of cloud pairs would then be gathered to statistically compare the seeded and unseeded cloud pairs.

Another approach, with fewer assumptions and more control over the experiment, is that of chaff tagging. The concept and initial experiments that demonstrate chaff tagging are described here. The experiments were conducted during the 1995 Arizona Program (Klimowski et al. 1998) in storm-embedded orographic gravity wave clouds.

2. EXPERIMENTAL DESIGNS FOR CHAFF TAGGING

A refined approach to the use of TRACIR is to tag but not fill the cloud volume with chaff. The presumption is that the volume of interest can still be tracked by following the chaff tags, *and* microphysical changes simultaneously can be monitored in the same cloud volume, between or near the tags, to avoid confusion with the chaff.

2.1 Designs for Stratiform Clouds

Two designs for monitoring seeding effects in stratiform clouds, including gravity wave clouds, are as follows.

Tagged circle. Using flares burning on wing racks or continuous-burning wing-mounted aerosol generators, an aircraft can seed around a complete circle in an advecting stratiform cloud, but simultaneously release chaff only on two arcs of the circle. Radar can then track the circle measuring the depolarization caused the chaff tags (i.e., their CDR signature), while simultaneously measuring the reflectivity (Z_e) changes due to seeding along the whole circle but particularly in the gaps between the chaff tags. This experiment might be enhanced by measuring changes in depolarization due to ice or enlarged drops caused, respectively, by glaciogenic or hygroscopic seeding. Since depolarization signatures are the order of 10 dB down from reflectivity signatures, the latter approach would be most effective if a shorter wavelength (e.g., K_a-band; 8.66 mm) radar were used to gain a higher sensitivity to the new, growing hydrometeors. This might be accomplished with an additional, synchronized radar or a dual-wavelength radar.

Parallel lines. Figure 11 in Klimowski et al. (1998) illustrates a well-defined line of chaff detected in CDR in a wave cloud. Similarly, parallel lines of chaff can be dispersed by an aircraft to bracket a seeding line where microphysical changes may be monitored as above. The chaff lines will advect with the cloud volume to continuously mark and isolate the position of the bracketed seeded line.

In the tagged circle or parallel lines experiments, the chaff tags or "brackets" should allow radar to unambiguously identify, follow, and monitor the treated region in clouds of a stratiform nature. Experiments of each of these types are described below.

2.2 Designs for Convective Clouds

Chaff tagging to isolate and monitor seeded volumes will be more difficult in convective clouds because of the more vigorous mixing. However, some potentially useful designs can be conceived.

Trailing plume tag. For cloud-base seeding in convective cloud updrafts, Reinking and Martner (1999) proposed that it might be possible to release a burst of chaff, cease the chaff release for several seconds, and release a second burst of chaff, seeding throughout. The chaff would mark the leading and trailing portions of the seeding cloud volume as carried by the updraft, and the induced microphysical changes between the marks could be monitored with the radar's Z_e and DR measurements without interference from the chaff. Under further scrutiny, this approach is weakened by the fact that the loft of chaff from a given release in a updraft is not complete, immediate and isolated; rather, the entrainment is gradual and continuous, such that the chaff leaves a trail to cloud base (Reinking and Martner 1996). The necessary modification to tagging updrafts is therefore to seed well into an updraft, and then mark the end of the seeded plume with a burst of chaff. The chaff will then show the loft and mark the lowest reaches of the seeded zone. Figure 1a shows the reflectivity of an orographic cumulus cloud; Fig. 1b shows a strong signature of a volume of the updraft in that cloud with a clearly defined top and filled with chaff (discussed as Fig. 10a,b in Klimowski et al.1998). The tagging concept is that the updraft in the cloud just above this chaff top may be inspected for microphysical changes due to seeding in the updraft just before chaff is released, such that the chaff follows the seeding material and its microphysical effects. The same approach might be attempted in seeding the tops of rising turrets from wing-mounted generators. Transport within and circulating around the turrets could be estimated in this way.

Flare curtain tags. Convective clouds are often seeded from their tops by releasing a curtain of droppable flares from an aircraft. In the Florida Area Cumulus Experiment (FACE), for example, cloud physics aircraft following a seeding aircraft through a convective updraft often did not find a seeding signature (in the form of high concentrations of ice crystals). Based on updraft speeds and the time elapsed between an aircraft release of nucleant and subsequent microphysical sampling, it was hypothesized and inferred from ice particle measurements but never proven that the flare material was rapidly lofted above flight level, such that the microphysical signatures of seeding were to be found above the sampling altitude. If, while releasing such a curtain of seeding material, the curtain were marked by dropping chaff flares at both ends, the chaff would show the movement and mixing of the seeded curtain, while the microphysical changes could conceivably be monitored between the flares. For comparison in paired clouds, the corresponding volume-filling experiment would be one of releasing chaff flares along with seeding flares across the entire curtain. Chaff flares can be manufactured, and both the tagging and volume-filling experiments are worth doing, due to the extensive use of droppable seeding flares.

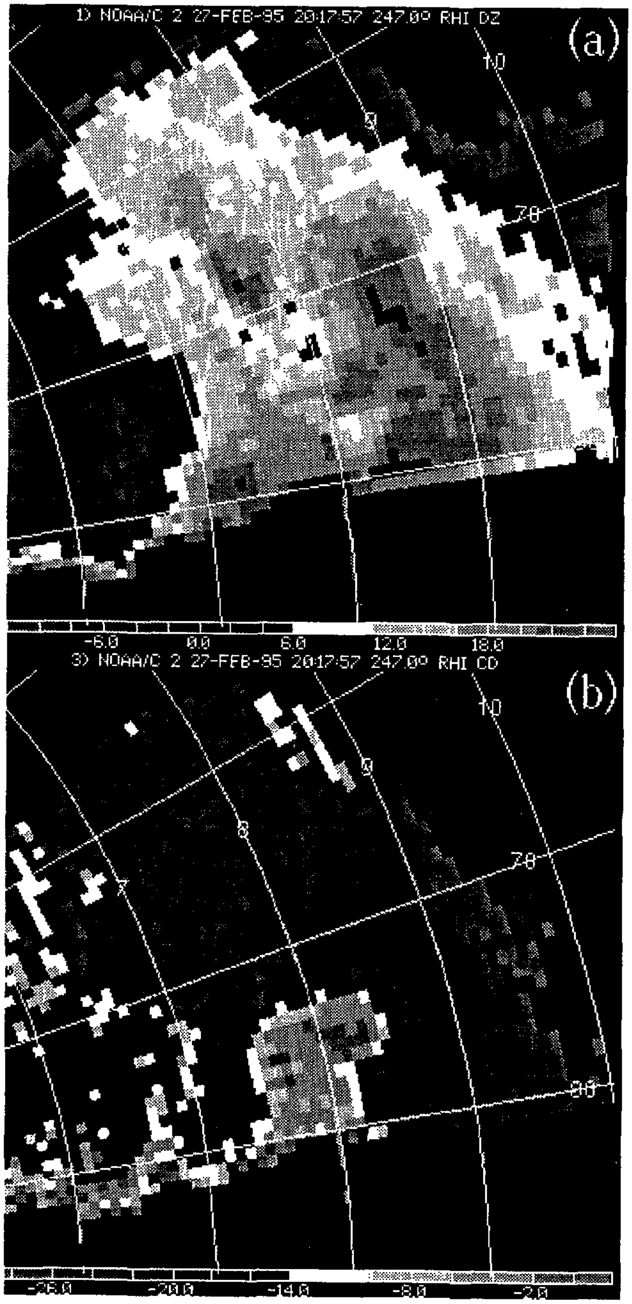


Fig. 1. Radar RHI scan showing the vertical cross-section or an orgraphically generated cumulus cloud. (a) the reflectivity (Z_e, dBZ) is greatest in the rainshaft, which is adjacent to (b) the updraft, clearly defined in CDR (dB) as it is filled with chaff (from Klimowski et al. 1998).

In summary, chaff tagging is a customized version of chaff tracking that marks cloud parcels and follows their transport while leaving the treated cloud volume between or adjacent to the tags open for radar examination of the hydrometeor evolution. A number of variations are possible on the suggested experimental designs.

3. CHAFF TAGGING EXPERIMENTS

Chaff tagging experiments were conducted in gravity wave clouds during The 1995 Arizona Program. The operational area is shown in Fig. 1 of Klimowski et al. (1998). The nature of the wave clouds is described by Bruintjes et al. (1994) and Reinking et al. (1999). The project cloud physics and chaff release aircraft, a Cheyenne II from Weather Modification, Inc., was based in Prescott, southeast of the project area. The NOAA/ETL dual-polarization (circular) X-band (3-cm) Doppler radar was used to apply TRACIR. It was located on the airport grounds at Cottonwood, at 1076 m AGL, in the Verde Valley, between the Black Hills and the Mogollon Rim. Mingus Mountain and the Black Hills form a NW-SE ridge immediately southwest and normally upwind of the Verde Valley watershed. The Mogollon Rim rises from the northern and northeast reaches of the Verde Valley and is the primary recipient of precipitation associated with orographic wave clouds, and the potential target area for precipitation enhancement by seeding (Bruintjes et al. 1994, Reinking et al. 1999). The two chaff tagging experiments described in the next sections demonstrate the technology as it was applied in this scenario.

4. A "PARALLEL LINES" TAGGING EXPERIMENT

A "parallel lines" chaff tagging / hygroscopic seeding experiment was conducted in a gravity wave cloud on 14 February 1995. The gravity wave had induced a well-developed foehn gap and a wave cloud deck downwind of the gap. The chaff release/seeding aircraft flew at wave-cloud base in the downwind edge of the gap. All airborne releases were made at ~2.4 km (8000 ft) MSL and 1.4 km AGL relative to Cottonwood Airport, approximately along the 140° radial from the radar, and across the wind. First, the aircraft released a line of chaff, and this began to be advected toward the northeast. Then, the aircraft reversed heading and a line was seeded with hygroscopic (NaCl) flares along the *same radial. The aircraft reversed heading* a second time, and a third line, this one of chaff, was released along the same radial. Thus, as one line was advected away from the release radial, it was replaced by another, to bracket a seeded line with two chaff lines. A log of these events and the detection of the chaff is presented in Table 1. The midway point of the seeding leg establishes a reference time of t_o = 0047 UTC.

Table 1. Log of controlled events and detection of chaff lines (UTC) for 14 February 1995 experiment.

0040-0044	~4 min chaff release, 1st line.
0042	First radar detection of chaff.
0045-0049	~4 min seeding line, 6 flares.
0047	Reference time, t_o.
0050-0056	~6 min chaff release, 2nd line.
0057-0102	Both chaff lines now very visible in sector scans.
0121	Chaff lines moving over Mogollon Rim.
0137	Last detection of chaff.

The clouds that persisted through this event are illustrated by the 004929 UTC (t_o + 2 min) RHI scan in Fig. 2, made with a second, cloud-sensing K_a-band radar. The experiment was conducted in the *cloud system below 4 km AGL, not the overriding* wave at 5-7 km AGL. At the lower level, the air in the gravity wave was descending down the mountain slope (from the left in the figure) and created a hydraulic jump just upwind of the radar. Beyond the foehn gap, this resulted in lift of as much as ~4 m s^{-1} and produced a low-level wave cloud which overrode small convective elements. The convective elements are evident and the wave cloud developed soon after 0059 UTC (Fig. 2a). The convection was also driven by the cross-valley gravity wave flow, which forced lifting up the next slope toward the Mogollon Rim. In the vicinity of the radar, a rotor developed, the return flow of which is evident in the velocity measurement (Fig. 2b). The low-level gravity wave cloud was quite diffuse (~ -22 dBZ) compared to the convective elements (≤ +10 dBZ). The wind in the wave reached ~8-10 m s^{-1} from ~225°, from a K_a-band velocity

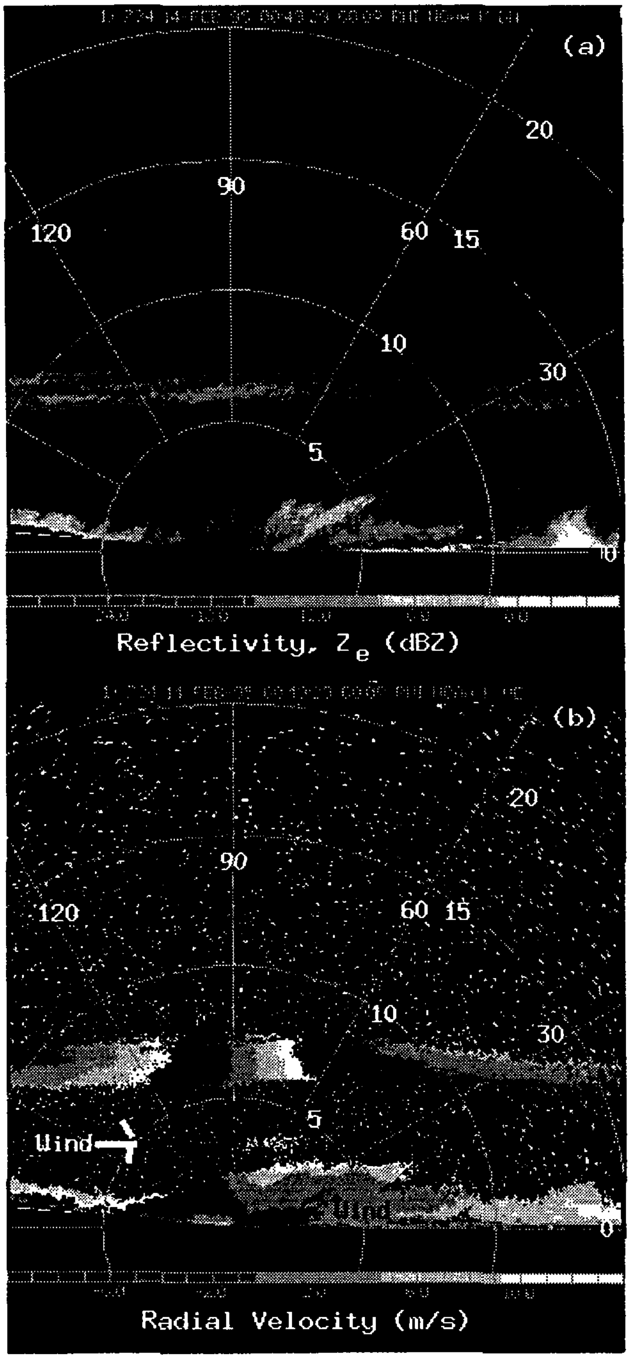


Fig. 2. Over-the-top radar RHI scan of (a) cloud reflectivity (Z_e, dBZ) and (b) radial velocity (V, m s^{-1}) from 60° azimuth at right (004929 UTC, t_o +2 min, 14 Feb 1995). Positive values of velocities indicate flow away from the radar. The wind was generally left-to-right except in return flow of the wave's rotor at the lowest levels.

azimuth display (VAD) scan at 0058 UTC. Undulations in the wave governed cloud top across the valley. In all, the system was much more complex than a stratiform wave cloud.

Each of the two chaff lines was visible in the CDR measurement within a minute after completion of their release into this cloud system. Fig. 3a shows both lines at 010120 UTC (t_o + 14 min), as indicated by the signatures in CDR $\geq$ -5 dB. None of the clouds was producing returns at -10 dB $\leq$ CDR $\leq$ +2 dB. Both lines were intact. The initial, northernmost chaff line (Table 1) had advected 12 - 13 km northeastward from the release radial, and the second chaff line had advected 6-7 km from that radial. By this time, dispersion was greater in the first line, due to its longer exposure after release. In the radar reflectivity, the chaff lines could generally be distinguished from the low reflectivity clouds that filled the space between them, but not from the heavier echo of the convective elements at the east and west ends of the lines (Fig. 3b). Just 2.5 min later, the northern chaff line began to be ingested into the convection, as indicated by a rapid widening of the line associated with convective elements.

The involvement with both the wave and the convection continued, eventually involving and widening the dispersion of both lines (011120 UTC or t_o + 24 min; Fig. 4a, b). A low-elevation RHI scan at 011355 UTC (t_o + 27 min) from horizontal to 15° elevation toward the 34° azimuth sliced vertically through portions of both lines (Fig. 5a,b); this shows that the chaff was lofted as high as 2.5 km AGL (about 1.1 km above the altitude of release in the foehn trough) in the convection, and stretched northeastward by the wind through the wave. Also, downwind, some of the chaff was driven back to lower altitude, evidently by the undulating wave action. By 0122 UTC, some of the southernmost line was still distinguishable as a chaff area some 5 km wide, but most of it was more widely dispersed in the combined convection and wave action and still highly visible in CDR, primarily between 10 and 40 km range along the 20° radial (not shown). The two lines were no longer separable.

In several plan position indicator (PPI) sector scans, there are possible hints of reflectivity enhancement along the seeded line, as bracketed between the two chaff lines (e.g., just north of the 90°radial at 10-13 km range in Fig. 3b). However, any seeding signature from enhanced drop concentrations was too subtle to positively identify against the highly non-uniform background of the existing clouds. In data processing, CDR was re-scaled from the +2 – -14 dB range for identifying chaff, to a -10 – -40 dB range to determine depolarizations by cloud particles, following the small chance that a line of no depolarization would be evident. Spherical drops like those that would be

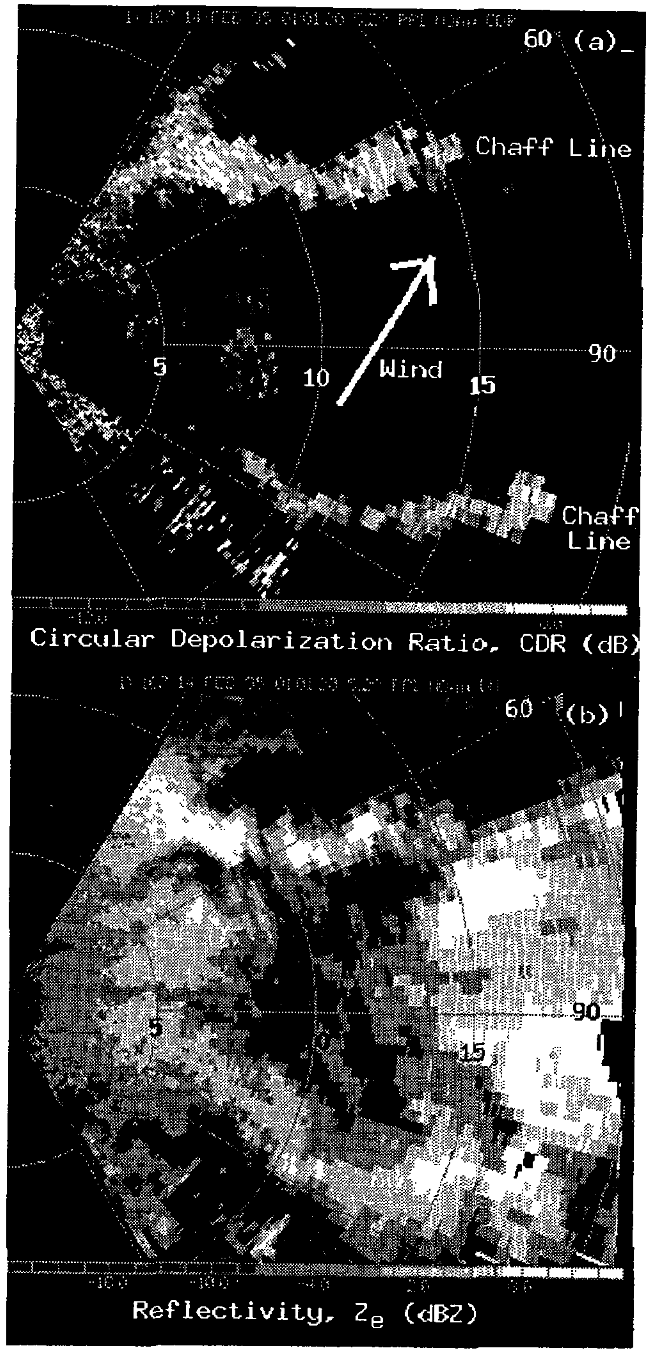


Fig. 3. X-band radar PPI sector scan at t_o + 14 min through 90° azimuth at 5.2° elevation of (a) CDR (dB) showing chaff lines and (b) corresponding cloud Z_e (dBZ). (5 km range rings; 010120 UTC, 14 February 1995.)

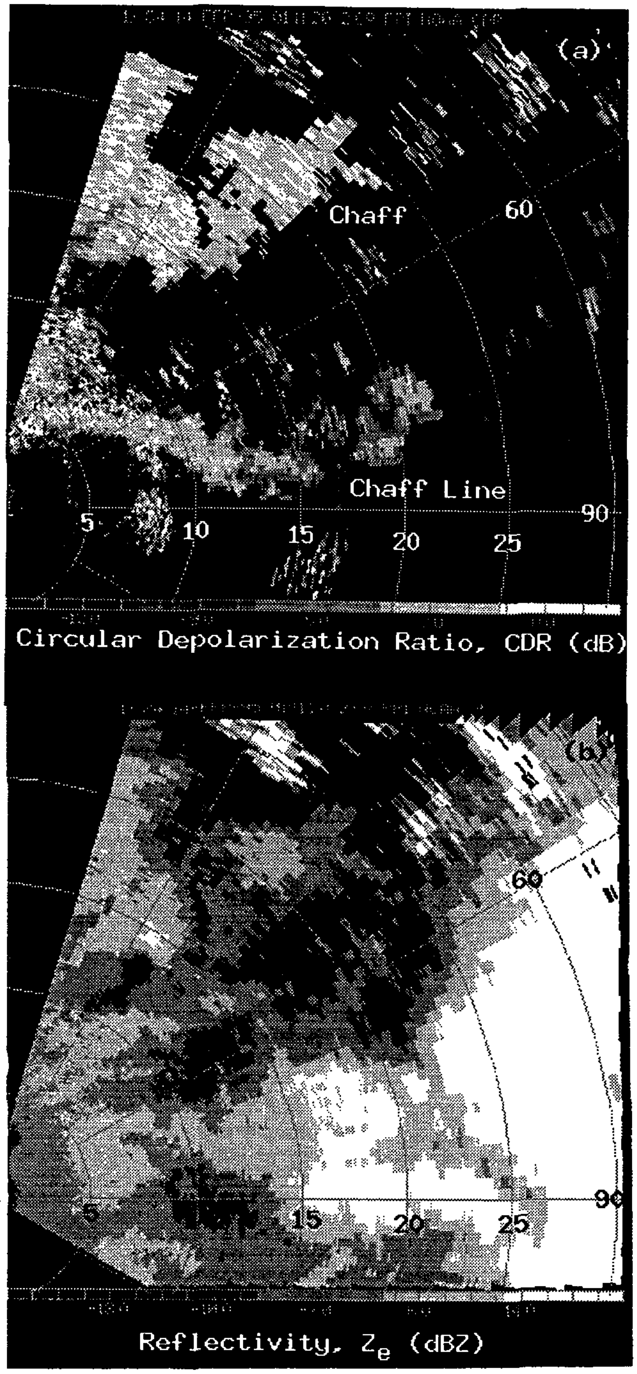


Fig. 4. X-band radar PPI sector scan at t_o + 24 min through much of northeast quadrant at 2.6° elevation of (a) CDR (dB) showing chaff lines becoming involved in convection and (b) corresponding cloud Z_e (dBZ). (5 km range rings; 011120UTC, 14 February 1995.)

created by hygroscopic seeding cause no depolarization, so their CDR value would be that corresponding to the cross-talk limit of the radar (~ -35 dB). No measurable CDR signatures were found in the areas between the chaff lines, either to identify a seeded line or complicate its identification. One cannot conclude that the hygroscopics had no effect, only that no effect was definitively observed. This experiment using hygroscopics is obviously difficult, but worth trying again in more uniform clouds. The use of parallel line chaff tagging is well demonstrated, nevertheless, particularly in defining where to look for a seeding effect.

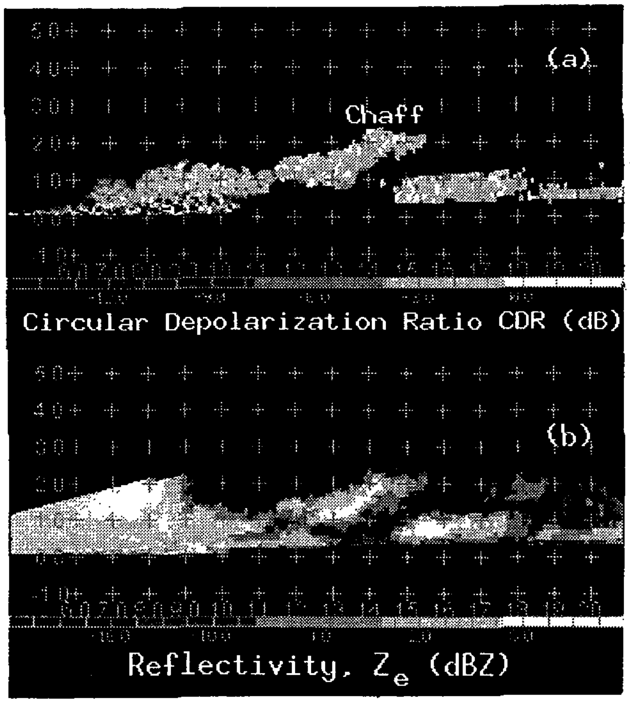


Fig. 5. X-band radar RHI scan from 0° to 15° elevation toward 34° azimuth (at right of figure) of (a) CDR (dB) showing vertical cross section of chaff lines stretched along the wind, and (b) corresponding cloud Z_e (dBZ). (5 km range rings; 011355 UTC, t_o + 27 min, 14 February 1995.)

5. A "TAGGED CIRCLE" EXPERIMENT

5.1 The Tagging and Seeding Operation

A "tagged circle" / AgI seeding experiment was conducted on 6 March 1995 in a purer gravity-wave cloud. This gravity-wave cloud of 4-5 km depth was embedded in the pre-frontal portion of a significant storm. The cloud is illustrated in Fig. 6 just prior to the tagged circle experiment, and the full event is detailed by Reinking et al. (1999). The cloud already contained some ice as well as new liquid water (LW) that was being condensed in the wave's

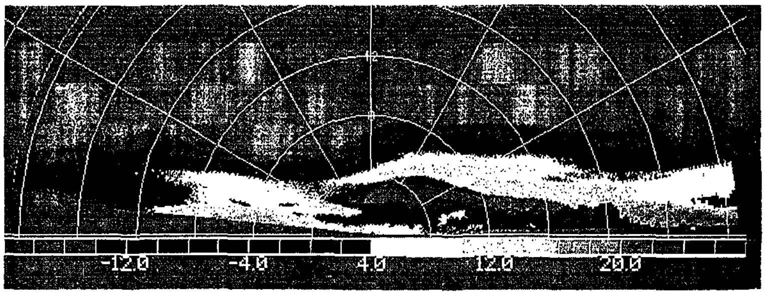


Fig. 6. Reflectivity Z_e (dBZ) of the gravity wave cloud from an over-the-top RHI scan just prior to treatment with chaff and AgI. The radar position is at center, at zero range (range rings have 4-km spacing).

updraft over Verde Valley. At cloud level near the upwind edge of the updraft, a circular airborne seeding path was marked with two arcs of chaff. While the arcs marked the seeded circle, enhancements in Z_e of the ring between the arcs were sought to identify enhanced ice concentrations produced by the seeding. Sector-volume scans with the radar were made to follow the tagged and seeded volume. A log of the controlled events for the AgI seeding case and reference times for analysis are presented in **Table 2**. Mid-points, the times halfway through the seeding and the chaff releases, were nearly the same, so one reference time, t_o, has been selected as the "initial time" for both of these events. In-rack, continuous burning flares (pressed composite pyrotechnics, active nucleant AgCL(I), a contact nucleus) were used to glaciogenically seed the wave cloud. The seeding track is shown as a helix in Fig. 7, in ground-relative coordinates. It was approximately circular in coordinates relative to the mean air motion through the cloud, as substantiated by CDR signatures from the chaff.

Table 2. Log and reference times (UTC) for controlled events for 6 March 1995 chaff tagging experiment.

Log:	
055335-055935	AgI seeding, 1st 5 flares, 6 min.
055720-055825	Chaff release, 1st arc, 1 min 5 s.
055940-060008	Chaff release, 2nd arc, 28 s.
060040-060240	AgI seeding, 2nd 5 flares, 2 min.
Reference times:	
055808 ± 4.5 min	Midpoint and timespan of AgI releases.
055844 ± 1.4 min	Midpoint and timespan of chaff releases.
055826	Designated reference time, t_o (midpoint of midpoints); ±5 min for AgI release; ±2 min for chaff release.

Chaff was released along the two arcs of the seeding circle, so as to mark the track but provide gaps in the circle where any seeding signature could be detected with radar without being confused with the chaff. As shown in Fig. 7, seeding was actually conducted over approximately 2.5 revolutions around the circle, so the entire circumference was seeded, despite a 1 min 5 s interval between flare sets. The seeding lasted 9 min 5 s. The upwind, straight-line gap in chaff was about 2.5 km long, and the downwind, straight-line gap was about 4 km long when created.

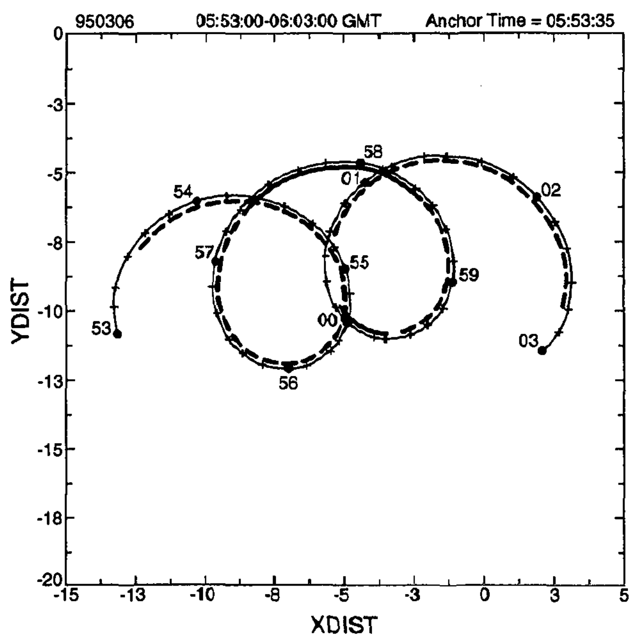


Fig. 7. Aircraft track for the release of chaff (solid) and seeding material (dashed, and solid of north chaff arc) on 6 March 1995, in ground-relative coordinates; distance X,Y (km) is relative to the radar site. The aircraft, flying in a circle, advected with the wind (from Bruintjes et al. 1996).

The seeding altitude varied between 4740 and 4910 m MSL, or 3674-3834 m above the radar site at 1076 m elevation; all of the chaff was released between 4750 and 4780 m MSL, or 3675-3705 m AGL. The cloud temperature varied by a few degrees along the seeding track due to an early climb and descent back to a near-constant altitude. The first five flares were burned between -6 °C and -8 °C, where the FSSP liquid water content (LWC) peaked at 0.20 and averaged 0.03 g/m^{-3}. The second five flares were also burned between -6 °C and - 8 °C, where LW peaked at 0.02 and averaged 0.01 g m^{-3} or somewhat less; these values may simply indicate instrument noise. Droplet concentrations, if any, were too small to be measurable (0555-0602 UTC in Fig. 8a-c) Consequently, the initial air temperatures were cold enough, but the drop concentrations and LWC were evidently too small to begin significant nucleation of the seeding agent in the foehn trough, during the release of material, before being ingested into the updraft where substantial condensation occurred to foster activation of the seeding agent and growth of the resulting ice crystals. In Fig. 8b, the LWC of ~0.25 with peaks of ~0.5-0.7 g m^{-3} were measured by the aircraft during penetrations through the wave crest (also see Bruintjes et al. 1996, Reinking et al. 1999).

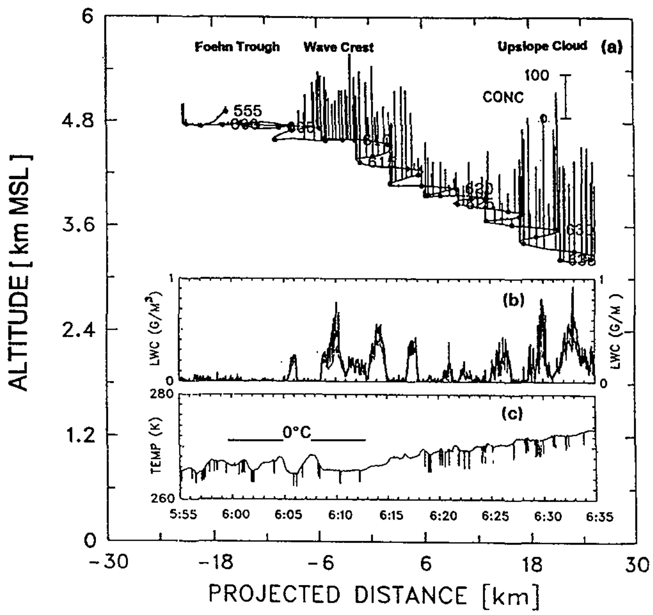


Fig. 8. Microphysical measurements from a west-to-east aircraft spiral transect and descent intersecting the foehn trough, wave crest, and an underlying upslope cloud between 0555 and 0635 UTC 6 March 1995: (a) cloud droplet concentration (CONC, cm^{-3}; bar scale superimposed on flight track plotted as altitude in km MSL vs. distance relative to the radar site at Cottonwood); with insets as a function of time approximately equal to the distance scale, of (b) LWC (g m^{-3}) from a King probe (light line) and an FSSP (dark line); and (c) air temperature (°K; spikes are due to radio transmissions and do not indicated temperature values).

5.2 Chaff Tracking

The seeding material and chaff were released 5-12 km south of the radar, between 14 km upwind and 3 km downwind of the radar (Fig. 7), Cloud-level advection at this time was ~20 ± 2 m s^{-1} toward aziumth ~80° (i.e., toward the ENE). The south arc of chaff was detected first, at 060543 UTC (~t_o + 7 min) at X,Y = +3 km,-10 km.

The radar first locked onto both chaff arcs during scan-volume 3, between 061129 and 061214 UTC, respectively 17.3 min and 9.5 min after the beginning and end of the seeding operation, or equivalently, at ~t_o + 13 min. Since their release, the north and south chaff arcs respectively had broadened to about 1 and 2 km at the radar elevation of strongest return (angle ß = 19°, CDR ≈ +4 – -8 dB, Fig. 9a); here the centriod of the seeded circle was X,Y ≈ +12 km, -6 km, at 13 km range and ~4.3 km *AGL*. At this time, the chaff was still sufficiently concentrated to produce a reflectivity signature of ~22 dBZ within the non-uniform cloud of ~ -10 – +14 dBZ at this altitude. However, no enhanced reflectivity due to crystals from seeding was detected in the chaff gaps (Fig. 9b).

Also at this time, the chaff signature was evident between ß = 10° and 25°, or ~ 2.3 and 4.7 km *AGL*. The chaff had spread through a 2.4 km vertical cloud volume, and some of it had ascended ~1.0 km above the release level in the gravity wave updraft. Single filaments of chaff nominally settle ~0.25 cm s^{-1}. The earliest portions of the chaff release would account for the highest altitude chaff. With settling accounted for, the ascent distance was ~1.23 km during the 15 min elapsed from the beginning of the chaff releases; this equates to an updraft of ~1.4 m s^{-1}. Clumps of chaff fibers settle faster and account for the lower reaches of the detected chaff volume; the 2.3 km vertical spread indicates a maximum chaff fallspeed of ~2.5 m s^{-1}, which would simulate 2 mm densely rimed crystals or graupel. (Pruppacher and Klett 1978, p. 343).

The wave updraft made substantial liquid available to activate the glaciogenic contact nuclei. Droplet concentrations of the order of 100-200 cm^{-3}

occurred with the LWCs 0.25-0.7 g m^{-3} through the wave crest. The temperature was more consistently -8 to -9°C through the crest. Given these conditions and the well-documented placement of the seeding agent, there is no question that ice was generated by seeding in the wave cloud.

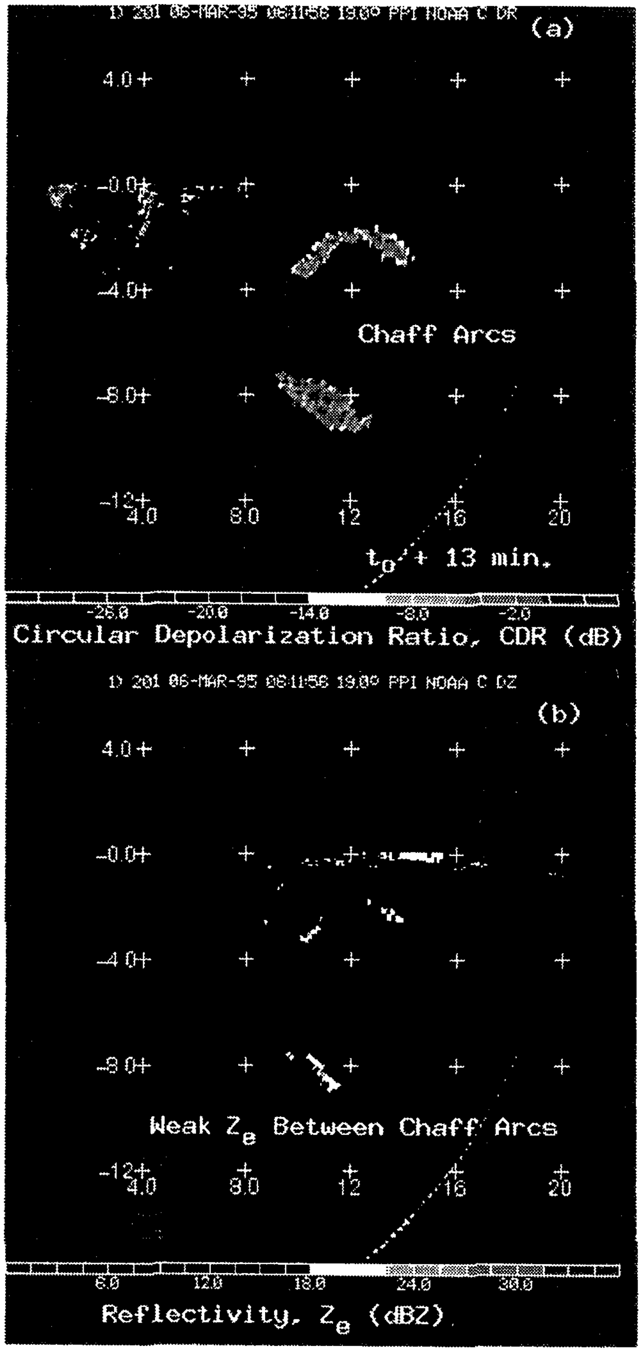


Fig. 9. Radar images for t_o + 13 min: (a) CDR (dB) of the two arcs of chaff; scale +4 – -32 dB. (b) Corresponding Z_e (dBZ) of cloud and chaff arcs. Cartesian grid is distance relative to the radar site; interval is 4 km (6 March 1995).

The first detection of what may be interpreted as a seeding signature from the resulting ice crystals on the seeded ring appeared between the chaff arcs (CDR, Fig. 10a) in the reflectivity signature in the downwind (east) gap at 062036 UTC (Fig. 10c). At t_o + 22 min, substantial time was allowed for AgI-nucleated crystals to grow to detectable sizes in concentrations above the background cloud. Indeed, the question arises, why would the ice-crystal production take so long? Contact nucleation is slow compared to other modes; it occurs continuously but gradually after release and takes on the order of 20 min to nucleate 100% of the active particles (W. Finnegan, personal communication). Also, production was likely slowed by a slow AgI nucleation rate at the -6 to -8°C temperatures, and initially by low LW contents as the seeding material (and chaff) were transported through the foehn gap before reaching the ascending condensation zone of the wave. At this detection, the circle of reflectivity in the gap between the chaff arcs was enhanced by about 10 dB over the surrounding cloud (Fig. 10c).

In subsequent scan volumes, Z_e was enhanced in both gaps between the chaff arcs (such detection depended strongly on radar elevation angle). For example, at 062810 UTC (t_o +30 min) at altitude ~3.4 km AGL, the chaff arcs are still lucidly identified in the CDR between ~ -4 and -12 dB Fig. 10b, and the enhanced Z_e in both gaps is evident in Fig. 10 d. On its downwind (east) edge, the seeding ring was merging with cloud of naturally enhanced reflectivity, but the seeding signature was also lucidly visible in the upwind chaff gap, where Z_e exceeded that of the surrounding cloud by as much as 15 dB.

Figure 11 summarizes the chaff tracking and observed radar reflectivity enhancements in the seeded ring for the entire case study. The position of the ring was established by the chaff arcs, observed as CDR $\geq$ -14 dB as they advected eastward. The highest altitude of positively identified chaff was noted to initially increase, then decrease with time, indicating passage through the wave and settling, as shown by the line with the interspersed letter C (for "chaff") in the figure.

Figure 11 also shows the vertical extent of the zone of enhanced reflectivity in the seeded ring, as a function of time (shaded area). To isolate this indicated seeding effect, the positions of the seeded arcs along the circle, in the gaps without chaff, were identified by projecting the curves of the chaff arcs through the whole seeded path, with consideration for the configuration of the initial near-circular aircraft track. The maximum reflectivity gradient across these

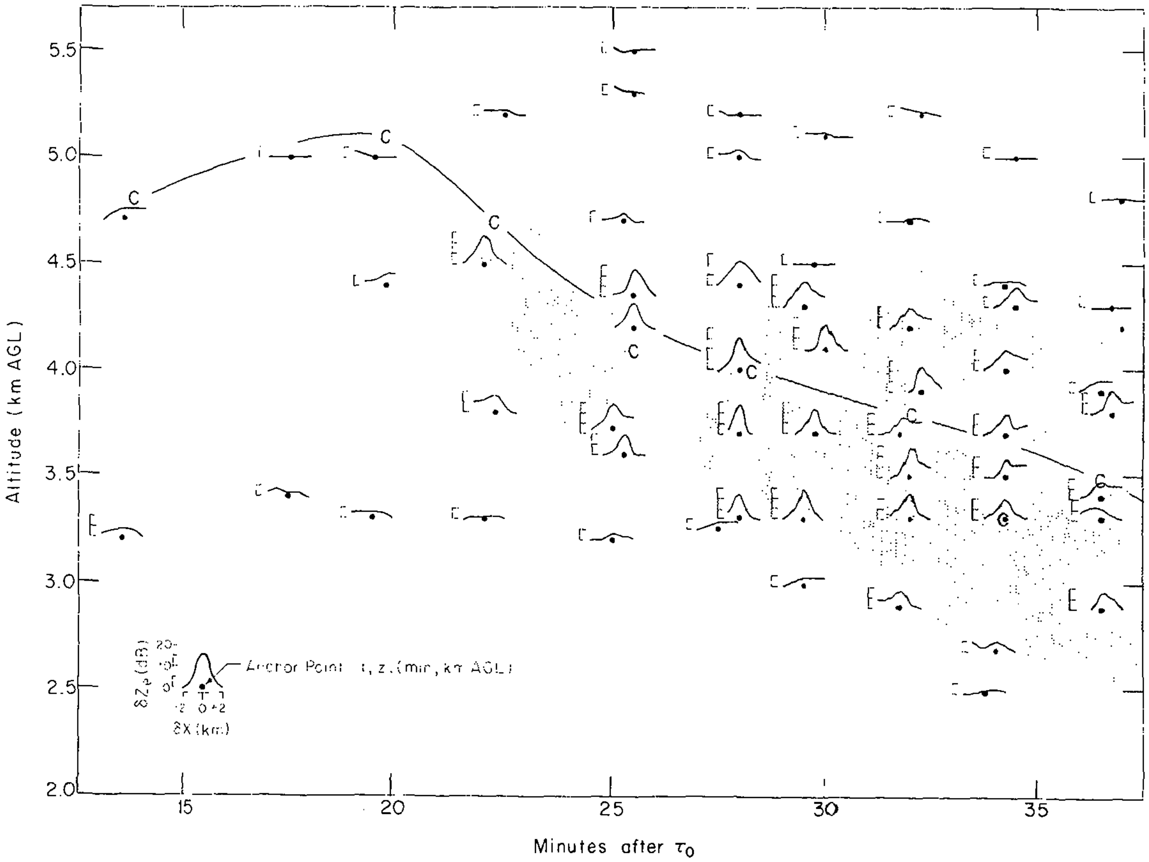
Fig. 10. (Color plate). In the top pair of radar images, CDR ≥-14 dB within the scale of +4 ≥ CDR ≥ -32 dB shows the two arcs of chaff at (a) t_o + 22 min and (b) t_o + 30 min; CDR ≈ -27± 3 dB along the seeded circle between the chaff arcs indicates pristine, new ice crystals from seeding (noted as "ice"). The corresponding bottom pair of images (c,d) shows reflectivity within a scale of $-20 \leq Z_e \leq +28$ dBZ and enhancements thereto (noted by "Z_e+") around the seeded circle, including the seeded path between the chaff arcs, where such enhancements also indicate increased ice crystal concentrations due to seeding. Cartesian grid with 4 km interval shows the distance relative to the radar site (6 March 1995).

north-south parts of the circle with seeding but no chaff was determined on approximately east-west line transects at positions of -2, -1, 0, +1, and +2 km from the seeded path on the circle. The minimum reflectivity along this transect was regarded as the background level, and this value, in dBZ, was subtracted from those at the other four positions which transected the seeded ring. Thus, the *reflectivity difference*, δZ_e (dB), was determined at each of five positions along each transect across the seed-only track (of course, this value was zero at the position of minimum reflectivity). The resulting individual, spatial distributions of δZ_e along the transects across the seeded arcs are presented as a function of time in Fig. 11, to show the enhancement of reflectivity on the seeded circle as peaks in the transects across the seeding path.

Fig. 11. (Below) Time-altitude plot (minutes after t_o, km AGL) of radar reflectivity enhancement of the seeding ring in the gaps between the chaff arcs. Note Key and text to interpret reflectivity transects used to make this plot. Curve connected by "C's" shows highest altitude of positive chaff identification (CDR ≥ -14 dB). The shading identifies the envelope of time and altitude where reflectivity was enhanced on the seeded circle by ~10 dBZ or more above minimum background along the transects.

Assuming that $\delta Z_e \geq 10$ dB occurring on the *quasi-circular seed-only track–but not elsewhere in the immediate vicinity*–is evidence of reflectivity enhanced by ice generated from seeding, the seeding signature first identified at t_o + 22 min as in Fig. 10c, is indicated in Fig. 11 between ~3.8 and 4.5 km AGL; this altitude range correlates well with the initial seeding altitude, allowing for the lift in the wave.

As noted earlier, the rise and subsequent descent of the top of the highest detectable chaff is indicated by the line connecting the "C's" in Fig. 11. After loft in the updraft, the top of the chaff descended faster and in time separated from the top of the δZ_e seeding signature, suggesting that the chaff settled somewhat faster than some of the nucleated ice crystals. This is physically probable. Nevertheless, Fig. 11 shows that the cloud volume with seeding signature deepened with time as the base of the seeding signatures descended, as expected with falling crystals. It is possible that the chaff would rime and increase its terminal velocity, but the same would happen with ice crystals, so any difference is assumed to be negligible. Thus the shaded area in Fig. 11 indicates the deepening with time of a snow plume from seeding, which was about 1.5 km deep ~35 min after the release of the AgI, when the seeding signature (δZ_e) began to be obscured by background



reflectivities. During this period, the seeded circle advected about 40 km to the northeast of the location where the cloud was seeded, indicating that the snow was deposited at the edge of the Mogollon rim 35-45 km east-northeast of the Cottonwood radar site.

This analysis based on Z_e is supported by some observations of an enhanced CDR that can be attributed to seeding-generated ice crystals. As noted above, Figs. 10a and b show the CDR signatures at 0620 UTC (t_o + 22 min) and 0628 UTC. (t_o + 30 min), respectively. Not only the chaff was detected (as CDR≥-14 dB), but also a CDR signature of ~-26 ± 3 dB appeared in the gaps between the chaff tags, along the seeded ring. The radar antenna elevation angles for these observations were 10.2° and 6.9°, respectively. In Fig. 10a, an enhanced CDR was *evident along the seeding circle within* coordinates X ≈ 25-26 km, Y ≈0- -5 km; this postion is in the eastward gap between chaff tags. In Fig. 10b, CDR was enhanced in both gaps between the tags, and most of the full seeding circle was evident.

A CDR signature of the order of -23 to -27 dB, at *low radar elevation angles*, is indicative of pristine columnar ice crystals, solid columns in particular, according to scattering calculations by Matrosov (1991). Depolarizations at such values by crystals are, fortunately, quite separable from chaff (whereas depolarization of the signal by planar crystals, for example, would be very similar to chaff *at the low radar elevation angles*). Although a shorter wavelength radar would afford better detectability of small ice crystals emerging from the seeding nucleation, the position and magnitude of the CDR signatures in the ring indicate that this enhanced depolarization is due to the same hydrometeors that also caused the enhanced *reflectivity in the ring*. There are patches of cloud with some CDR signatures from other particles, but the patterns of the signatures, filling the path along the ring of seeding, are in themselves quite convincing evidence of ice crystals from the seeding process. Since for chaff, CDR ≥ -14 dB and usually CDR ≥ -5 dB, a re-scaling of CDR in Fig. 10b to the -22 – -32 dB range eliminated the chaff signature and isolated the signatures of the ice crystal *within chaff arcs* as well as between the chaff arcs. The CDR values of ~ -28 - -21 dB in Fig. 12 within the areas of the chaff tags and between them indicate enhanced ice within the chaff tags as well as between them, as it should be since the whole ring was seeded.

After seeding and chaff release, the aircraft continued to circle and attempted to stay with the seeded plume, although a post-facto examination indicates it gradually descended below at least the core of the plume. Ice crystal imagery from the PMS 2D-C probe on the aircraft showed columnar crystals occurring by 0625 UTC (t_o + 27 min; Fig. 13). The crystals imaged appeared to be of a transitional solid column-needle growth habit, which is in accord with the cloud temperatures of ~ - 6°C in the foehn trough where seeding took place, and ~- 8°C through the crest of the wave where crystal growth was promoted. Prior to that, small crystals of undecipherable types were emerging. Some graupel can also be noted in Fig. 13. As noted above, the wave cloud passing though the foehn trough and into the updraft already contained ice. Polarization studies with the accompanying K_a-band radar from the storm event before and after the seeding experiment indicate that the ice passing through the trough was dominated by columnar crystals which were transformed into more spherical, less depolarizing forms, presumably by riming to graupel with liquid condensed in the wave updraft; such crystal detection and transformation is documented by Reinking et al. (1996, 1999) . Thus both columnar crystals and graupel are likely responsible for much of the background reflectivity across the field of observation. However, since the conditions for formation were the same for the ice nucleated by seeding material, the background does

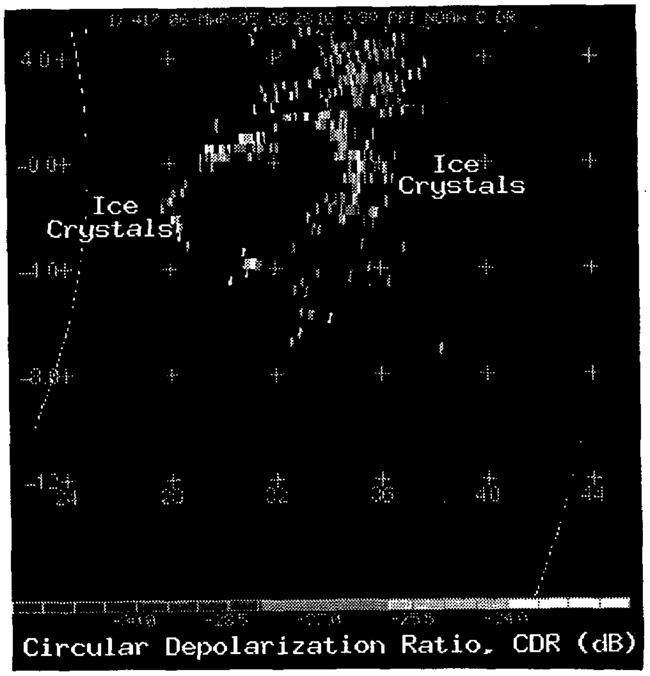


Fig. 12. Radar image of CDR (dB) re-scaled to a range of -22 to -32 dB to delete the signature of chaff and capture the signatures of pristine columnar ice crystals for t_o + 30 min, corresponding to Fig. 10b. Ice crystals around the entire seeded ring are indicated.

not preclude enhancement of ice in the form of columnar crystals and then formation of graupel by the same processes as a result of seeding, and thus appearing along the seeded ring.

A more thorough analysis of the aircraft sampling relative to the seeding event may further clarify the ice processes and seeding effects, and is the subject of a separate study. Here, the objective of demonstrating the utility of chaff tagging has been accomplished.

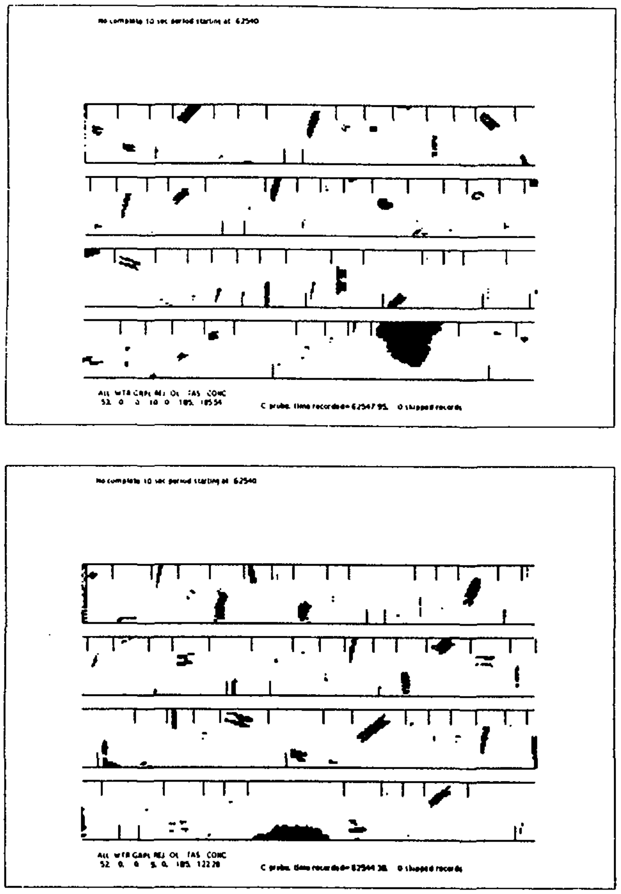


Fig. 13. PMS 2D-C images of graupel and columnar ice particles from aircraft samples in the downwind reaches of the wave cloud at 0625 UTC (sample volume width: 800 μm).

6. CONCLUSIONS

To measure transport and dispersion in cloud and simultaneously examine unambiguously the microphysical evolution in the same cloud volume, a refined approach to TRACIR has been devised. The modified approach is to tag but not fill the cloud volume with chaff. Chaff tagging marks cloud parcels, allowing their transport and mixing to be followed while leaving the treated cloud volume between or adjacent to the tags open for radar examination of the hydrometeor evolution. Some experimental designs for chaff tagging have been outlined for stratiform/wave clouds and cumuliform clouds. The two case studies in storm-embedded wave clouds demonstrated the principles of chaff tagging.

In one, parallel lines of chaff were released to bracket a line of hygroscopic seeding in a wave cloud system confounded by underlying convective cells. The lines and their evolution were clearly tracked in the chaff CDR signatures, which could be followed for nearly 1 h. The hygroscopics increase drop concentrations and may widen the drop size distribution, so an enhanced reflectivity is likely the best radar parameter for finding a seeding signature. Such detection may be difficult even in uniform clouds, but the experiment was worth trying. The complexity of the cloud in this particular case, caused by the intrusion of some convection into the stratiform wave cloud, precluded finding good evidence of a line of enhanced reflectivity, and thus a seeding signature. This suggests that chaff tagging is likely to hold more promise for stratiform clouds than convective clouds, although certain methods of tagging in convective clouds should certainly not be ruled out without trails.

In another case, a purer gravity wave cloud was seeded with AgI from an aircraft along a circular path. The path was marked with arcs of chaff, and tracked with circular-polarization radar. After ~20 min, radar reflectivities indicated by their position to be enhanced by seeding were detected on the advecting circle in the gaps between the chaff. A seeding signature was taken as a reflectivity enhancement of at least 10 dB above the background cloud. The signatures persisted in the cloud for more than 15-25 minutes, identifying a deepening snow plume that was tracked to near the elevated ground of the downwind mountain rim. Notably, it was also possible to divide the scale of circular depolarization ratio, such that CDR $\geq$ -14 dB isolated the chaff and -32 $\leq$ CDR $\leq$ -22 isolated the columnar ice crystals on the seeding ring that were evidently produced by the seeding and were documented with aircraft measurements. Aircraft-produced ice particles (APIPS) have not been considered, but any ice of such origin would have the same effect as ice from AgI and would not change the result of this demonstration.

Quantitatively, miniscule fractions of the storm volume and total precipitation were affected by this experiment, but a capability for producing, observing, and tracking seeding effects in gravity wave clouds was effectively demonstrated.

More experiments of this type should be conducted. With chaff tagging, the assumption that seeding nucleants activate in natural clouds just as they do in laboratory clouds can be tested. Using stratiform clouds as natural laboratories, adjacent tagged circles could be seeded with differing nucleants and the results compared. For example, fast-acting vs. slow-acting chemical complexes of AgI could be compared. A measure of dilution is also possible in the radar signatures from chaff, so estimates of nucleation activity may also be derived. The tagging technique is equally applicable to following cloud parcels to determine their kinematic and microphysical evolution resulting from ingestion of natural or anthropogenic aerosols of any kind. Such chaff-tracking experiments on PBL venting by cumuli may become important, since pollution effects on rain and water resources are a rising international concern.

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Comment on
"An Application of Hygroscopic Flares – A Single Case Study",
by Henderson, Wood and Newsom

Jean-Francois Berthoumieu
Association Climatologique de la Moyenne Garonne
47520 LE PASSAGE D'AGEN
France

and

Griffith Morgan
Thunderstorm and Hail Prevention Research Center
ERSA/CSA
Cervignano
Italy

In a short paper (accompanied by a cover photo with explanation) describing a single case study, Henderson, et al. (1997; hereafter HWN) raised the spectre of hail production as a consequence of seeding a cumulus cloud with flare-produced hygroscopic salts. We have read that article with great interest and arrive at a radically different conclusion. Though it is not possible to prove anything with a single case study, we could argue that the described case is a heuristic demonstration of the effectiveness of the hygroscopic flares in reducing damaging hail.

The principal hypothesis under which most hail prevention cloud seeding has been performed, over many years, has involved the generation, usually by seeding with ice-forming nuclei such as silver iodide, of large concentrations of graupel and small hail, to create a condition of "beneficial competition". This is expected to limit the growth of the individual hailstones to less than about one cm in diameter, so that they will melt before reaching the ground (see, for example, Ludlam, 1958, or Sulakvelidze, 1966). Hail of the sizes (5 to 7 mm diameter) reported in the article by HWN to have fallen on high ground will melt before falling to elevations of a few hundred meters above sea level. On many thunderstorm days in northern Italy, small hail and graupel (often in large amounts) are reported from the mountain weather stations in the Alps, though hail does not fall from thunderstorms in the lower, agricultural areas on most such days. The same is true over the Pyrenees and the adjacent plains.

HWN could only give qualitative descriptions of concentrations, such as "a substantial amount" of snow pellets and hail, or the ground being "white with hail." We infer from the descriptions given that the seeding successfully created large concentrations of ice particles in the cloud. This could be taken as confirming the observation by Mather (personal communication), based on flights with an instrumented Learjet in flare-seeded clouds, in South Africa, of (unexpected) high concentrations of ice particles, far beyond what have been experienced there in unseeded clouds, at the -10°C level. It further might confirm the observation of one of us (JFB), in France, of the generation of ice needles in clear air at -2°C and 95% relative humidity following seeding with a flare. These observations have not been explained, but have played a role in our decisions to pursue research into the effect of hygroscopic flare seeding on hailstorms. The report by HWN further encourages us in that.

The reported rate of seeding in the HWN case study was rather low compared to what has been used in the hail prevention project which was carried out by one of us (JFB) near Agen, France, using hygroscopic flares to seed warm-based (>O°C) thunderstorm clouds (the primary objective of the seeding is to accelerate the coalescence process). The observations of HWN may shed some light on the practical question of seeding rates with hygroscopic materials, in that a spectacular effect was possibly produced with a small amount of material. In the French hail prevention trials, two 1000g (similar to those used in South Africa and in Mexico for rain enhancement) are used, every four minutes, flying in the laminar inflow of a storm, a region about two to three km wide. The flare used produces most of its particles in the 0.3 to 10 micrometer diameter range. The posi-

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tion of the seeding, the quantity and the dimensions of the salt particles are crucial to producing a change in the microphysical properties of the warm part of the cloud, and surely also in the supercooled part.

The non-randomized trials of hygroscopic flare seeding for hail prevention in the vicinity of Agen, France, have not yet been fully analyzed, but preliminary results suggest a strong positive effect for hail suppression. It is planned, for the summer of 1999, to make cloud-physical measurements in flare-seeded clouds in northeastern Italy, and perhaps confirm the existence of the effects reported by HWN.

References

Henderson, T.J., J.M. Wood, and D.L. Newsom, 1997: An application of hygroscopic flares -- a single case study. *The Journal of Weather Modification,* Vol. 29, no. 1, pp. 90-94.

Ludlam, F. H., 1958: The hail problem. *Nubila,* Anno 1, *N.* 1, 96 pp.

Sulakvelidze, G.K., 1967: *Rainstorms and hail.* Israel Program for Scientific Translations, Jerusalem 1969, 310 pp.

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REPLY

Thomas J. Henderson
Atmospherics Incorporated
Fresno, California 93727

Berthoumieu and Morgan (hereafter BM) have raised a question about our previous paper (Henderson, et al; 1998 hereafter HWN) in which we suggested the observed graupel and hail production may have a consequence of seeding a cumulus cloud with pyrotechnic generated hygroscopic salts. BM argues that the described case is actually a heuristic demonstration of the effectiveness of the hygroscopic material in reducing damaging hail. BM continues with a description of the principal hypothesis of which most hail prevention cloud seeding programs have been performed over many years; "namely the generation, usually by seeding with ice forming nuclei such as silver iodide, of large concentrations of graupel and small hail, to create a condition of beneficial competition". We thank BM for their insights to hail formation and growth, including a refresher on the seeding hypothesis, as well as a few preliminary thoughts in regards their field observations of seeding cases.

First, beginning with one of our operational hail suppression programs in the mid-1970's, we essentially abandoned any further mention of "beneficial competition", particularly any reference to the intended generation of large concentrations of graupel and small hail as BM suggests. Instead, we chose to reference our hypothesis as "limiting supercooled liquid water (LSLW)". We have continued this reference since that time. The difference between "beneficial competition and "LSLW" is subtle but extremely important to the field of operational hail suppression, and quite likely to the scientific community as well.

The fundamental ingredient of *primary* concern in our hail reduction hypothesis is not hail embryos, but rather the actual concentration of supercooled liquid water within that specific cloud volume which allows the birth and growth of hailstones. Additionally, there is still considerable uncertainty within the scientific community as to whether or not silver iodide actually enhances the production of hail embryos, or simply produces billions of very tiny ice crystals from the supercooled liquid cloud droplets. These tiny ice crystals are not good hail embryos.

The admission of any intentional production of hail embryos such as graupel, frozen droplets, and small hail, raises a specter (a BM word choice) extremely unfavorable to the operational hail suppression community. Because supercooled liquid water is the fundamental requirement for the formation and growth of hailstones, attempts to limit this ingredient can only enhance the concept of less and smaller hail at ground level. The admitted artificial production of hailstone embryos is counter-productive and, in our view, unnecessary for the development of an acceptable hail suppression hypothesis.

Second, our described single seeding event was not associated with a field research program. Rather, it was one of several thousand seeding events within our operational precipitation enhancement programs conducted mostly, but not exclusively, with silver iodide. Within those silver iodide seeding events focused on orographic cumulus cells, it is rare to observe graupel or small hail falling at the same elevations as noted in the summarized case.

One of our very important concerns within the hail suppression community is that, in many large hail producing cumulus clouds, the intentional production of hail embryos may be insufficient to actually decrease average hail sizes at ground level *enough* to significantly decrease crop damage. Often in agricultural areas, the most damaging hail comes from high concentrations of smaller hailstones driven by wind, rather than a much lower concentration of very large hailstones. Intentionally increasing hail embryos is a scary thought.

In their Comment, BM proceeds with some of their interesting observations of seeded events in France, Italy and South Africa. They are important observations and we appreciate their inclusion. Additionally, we strongly support their plan to proceed with "cloud-physical" measurements in 1999 as part of a flare-seeded program in northeastern Italy. We look forward to summaries of their observations, further cloud physics measurements, and the apparent results from the applications of hygroscopic seeding materials by the BM and JFB groups.

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DEVELOPMENT OF STANDARD PRACTICES FOR DESIGNING AND CONDUCTING WEATHER MODIFICATION PROJECTS

by
George W. Bomar
Texas Natural Resource Conservation Commission
Austin, Texas

Abstract. The American Society of Civil Engineers' Atmospheric Water Management Standards Committee has begun the process of formulating a set of standard practices for designing and implementing various kinds of weather-modification projects. Subcommittees are working on standard practice documents for precipitation-enhancement, hail-suppression, and fog dispersion. A Standards Committee balloting process will be initiated in 1999 to finalize these standard practice documents, with the aim of publishing the documents once the full membership of the ASCE has engaged in a review and comment process on the documents.

1. INTRODUCTION

Because it is viewed increasingly for its potential to augment the supply of fresh water as well as a reliable means for mitigating certain hazardous weather conditions, the use of weather-modification technology has flourished in recent decades. Cloud-seeding projects have sprouted throughout the semi-arid western U. S. in hopes that they will prompt moisture-laden clouds to process and deliver increased amounts of rain water and snowfall. Other projects, particularly in vulnerable areas of the Great Plains, have embraced the seeding of clouds to lessen the likelihood of ruinous hail from large thunderstorms or to dissipate dense fog to facilitate the movement of air traffic.

This increased usage of weather-modification technology prompted the American Society of Civil Engineers (ASCE) to establish a Weather Modification Committee, whose responsibilities included the development of a manual of professional practice for augmenting precipitation (ASCE, 1983). Subsequently, a task committee of the ASCE Climate and Weather Change Committee expanded and updated this report (ASCE, 1995). This revised manual, *Guidelines for Cloud Seeding to Augment Precipitation* (ASCE Manual No. 81), provides water-resource managers and others who might become involved in the decision-making process for implementing a cloud-seeding project with the necessary guidance.

With specific guidelines in place for conducting cloud-seeding operations to augment precipitation, the ASCE's Atmospheric Water Management (AWM) Standards Committee in 1996 began to develop a set of standard practices for designing and implementing these cloud-seeding projects. The AWM chose to develop a set of standard practices, not only for the enhancement of precipitation (rainfall and snowfall), but for the suppression of hail and the dispersal of fog as well. The Committee established a subcommittee to originate a draft document of standard practices for each of the three facets of present-day weather modification technology.

The three subcommittees of the AWM Standards Committee in recent months have written draft documents on standard practices for precipitation augmentation, hail suppression, and fog dispersion. This paper gives a description of these documents as well as the procedures to be followed in order to finalize and, thus, qualify them for publication by the ASCE.

2. CONTENTS OF THE DOCUMENTS

Each of the three documents provides an historical overview of the evolution of the technology of cloud modification applicable to each of the objectives.

The documents also summarize current perceptions of the respective technologies. Policy and capability statements issued by the American Society of Civil Engineers, American Meteorological Society, World Meteorological Organization, and Weather Modification Association are cited as summaries of present opinions on the scientific establishment of the technologies.

The user of the standards documents will also find a succinct description of the primary requisite atmospheric conditions that are conducive to the development of fog and rain-bearing and hail-producing thunderstorms. Various concepts that explain why some clouds materialize to pose a fog problem or develop to produce rainfall or hailfall are discussed to a limited extent. The role of numerical cloud models in characterizing the dominant microphysical and dynamical processes operative within fog and convective clouds is also covered succinctly.

The bulk of the documents addresses the general requirements for the conduct of cloud-seeding or fog-dispersal operations. The guidelines provide an extensive treatment of such considerations as selection of seeding agent(s), delivery systems, support equipment, targeting concepts, recognition of seeding opportunities, and personnel requirements.

Some limited discussion is provided on various legal and environmental considerations to be factored into designing and implementing weather-modification operations. Each document has a section containing suggestions on steps to be taken to ensure public safety and mitigate public concerns.

The issue of how to evaluate weather-modification activity is addressed in each of the three documents. Constraints on project design are discussed, including the merits and disadvantages of both randomized and non-randomized activities. Evaluations that shed much insight on the efficacy of weather-modification approaches may use either direct (pads, gages) or secondary (insurance, crop-yield) data.

Finally, each document provides a comprehensive glossary of acronyms and terms as well as a thorough listing of references.

3. PROCESS FOR ADOPTION OF A STANDARD

The ASCE Atmospheric Water Management Standards Committee will initiate certain ASCE-prescribed procedures in 1999 that will eventually lead to approval and publication of each of the three standard-practice documents.

3.1 The Balloting Process

Any standard proposed for either precipitation-enhancement, hail-suppression, or fog-dispersion will have been discussed at a meeting of the ASCE AWM Standards Committee. A majority of those present for the meeting must approve, by motion, for the standard to be submitted to a committee letter ballot. The letter ballot, including abstentions, must represent not less than 15 Committee members, or at least 65 percent of the approved AWM Committee membership. Of all the votes cast during the ballot process, affirmative votes must be at least 75 percent.

The period for letter balloting, to be established by the Committee during the spring of 1999 for at least one of the three draft documents, must be at least 30 days in duration and cannot begin before at least 30 days from the time the draft document is mailed to Committee members. Within 30 days of the end of the voting period, all letter ballots will have been counted and reported. Results of all letter ballots will remain confidential to Committee officers until the voting period is closed.

In the event negative votes on any draft document are cast, certain procedures will be followed by the Committee chair, who will review each negative vote with the member so voting. Any and all negative votes must be accompanied by an explanation, as well as a suggested change, to overcome the negative vote. Otherwise, the negative vote will be regarded as non-persuasive and will be reported by the chair as unresolved.

If a modification (other than editorial) to a proposed standard is required, the modified standard will be evaluated by the Standards Committee and voted on in another committee letter ballot. If the modified standard is not accepted, the negative vote in each instance will be designated non-persuasive and the negative voter so notified. If the modified standard is accepted, however, it along with commentary is then sent through the AWM Standards Committee to the Codes and Standards Activities Committee (CSAC) of the ASCE.

Once the CSAC reviews and approves the documents to ensure their compliance with ASCE rules, the proposed standards document can be sent to the full membership of the Society. A notice of the availability for review of the proposed standard with commentary is published in the *ASCE News*. A notice of the availability of a public ballot on the standard, and notification of the closing date for the balloting process, are also included in the *ASCE News*. The commentary is furnished with the public ballot for information and comment but is not to be voted on.

Anyone who is not a member of ASCE can request a ballot and participate in the public ballot on the standard. Voting on the public ballot will close six weeks after the notice is published in the *ASCE News*, with all ballots sent to ASCE headquarters, where they will be counted within 30 days of the end of the voting period. Any negative votes will be processed by the Standards Committee in the same way (described above) that was followed when Committee members engaged in the balloting process.

Once due process is afforded for all negative votes cast, the CSAC will determine whether the standard and commentary were developed in compliance with ASCE Rules. Then, and only then, may the CSAC submit the standard to the American National Standards Institute for approval as an American National Standard.

3.1 Proposed Schedule for the Balloting Process

The AWM Standards Committee expects to initiate the balloting process on one, or more, of the standard-practice documents in 1999. Whether any of the three documents can proceed to the CSAC for notification in the *ASCE News* before the end of 1999 will depend on the nature, and number, of negative votes cast by members of the full Standards Committee once the balloting process is underway during the spring/summer of 1999.

4. REFERENCES

ASCE, 1995: *Guidelines for Cloud Seeding to Augment Precipitation*, ASCE Manual of Professional Practice No. 81, American Society of Civil Engineers, New York City, 145 pp.

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